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NEUTRON CAPTURE GAMMA RAYS FROM LITHIUM, BORON, AND NITROGEN[1]

G. A. BARTHOLOMEW AND P. J. CAMPION

ABSTRACT

The neutron capture γ-rays from Li^7, B^{11}, and N^{15} have been studied. In Li^7 γ-rays are observed at 7.26 ± 0.03 Mev. and 6.78 ± 0.05 Mev. In B^{11} six γ-rays are detected. The spectrum is consistent with $J = 7/2+$ for the capturing state. In N^{15} six previously unreported γ-rays are detected. Estimates of thermal neutron radiative capture cross sections are: Li^6, 0.028 ± 0.008 b.; B^{10}, 0.5 ± 0.2 b.; and N^{14}, 0.08 ± 0.02 b.

INTRODUCTION

This paper contains the results of a study of the neutron capture γ-rays from a group of three product nuclei, Li^7, B^{11}, and N^{15}, for which the predominant mode of decay is particle emission. Because of this competition the capture γ-ray spectra, for Li^7 and B^{11} in particular, are very weak and difficult to detect. From a study of the spectra it is possible to derive, in addition to some knowledge of the decay schemes, an estimate of the radiative capture cross sections for thermal neutrons in all three nuclei. The spectrum of nitrogen has been investigated in earlier experiments at this laboratory (Kinsey, Bartholomew, and Walker 1951) and the present measurements with improved apparatus were undertaken to clarify certain details of the spectrum remaining from that work. The capture γ-rays from lithium and boron have not been previously reported.

The pair spectrometer and the details of the method of detecting and measuring neutron capture γ-rays have been described in an earlier publication (Kinsey and Bartholomew 1953). In order to measure the weak γ-rays from lithium and boron the spectrometer was generally operated with high transmission and poor resolution, viz. with a line width of 150 kev. For the measurement of the relatively more intense nitrogen spectrum the line width was 100 kev. Certain regions of special interest in the spectra of boron and nitrogen were examined with the aid of a modified slit arrangement (Bartholomew, Campion, and Robinson, unpublished) covering the electron counters in the pair spectrometer. These apertures have the effect of improving the resolution

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by largely eliminating the low energy tail of the coincidence peak at the cost of some loss in transmission.

The lithium and boron samples, which consisted of chemically pure Li_2CO_3 and B_4C in powder form, were enclosed in cylindrical graphite containers with 1-inch thick walls. The thick walls served to ensure that the entire surface of the sample, where most of the neutron flux is absorbed, was within the field of view of the spectrometer as defined by the collimating apertures placed in the experimental hole of the pile. In order to identify the weak radiations from lithium and boron in the presence of the carbon capture γ-rays and background radiations from the experimental hole, a study of the spectrum obtained with an empty container was made in the energy region between 3.0 and 11.5 Mev. The line width for this measurement was 150 kev. The background spectrum is shown in Figs. 1 and 3 in which some γ-rays emitted from the collimating apertures and structural materials in the experimental hole are identified.

LITHIUM

The lithium capture γ-ray spectrum was examined between 6 and 8 Mev. The spectrum obtained is shown in Fig. 1. Two γ-rays at 7.26 ± 0.03 and 6.78 ± 0.05 Mev. were detected. These radiations may be assigned to the transitions between the capturing state in Li^7 and the ground and first excited states respectively as shown in Fig. 2. No attempt was made to detect γ-rays

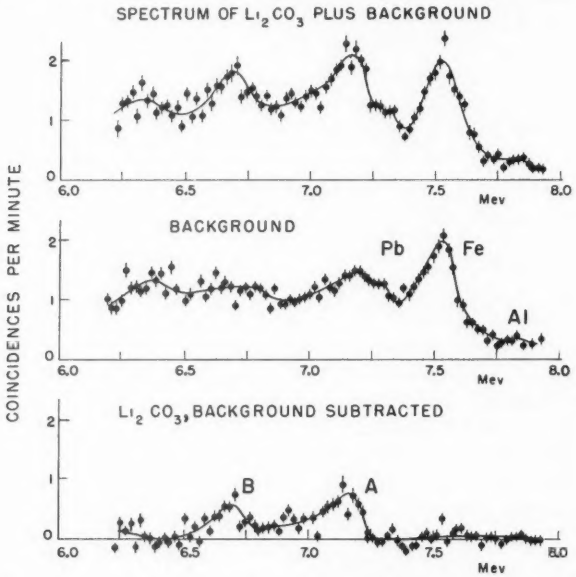

FIG. 1. γ-Ray spectrum from lithium. The top curve shows the spectrum including background. The bottom curve is obtained by subtracting the smoothed background spectrum shown in the middle curve.

at 2.63, 4.13, and 4.61 Mev., which might be emitted in transitions to the excited state at 4.61 Mev. and from it to the lower states, partly because these radiations would be expected to be relatively weak and also because the low counting efficiency of the pair spectrometer at these energies would make their detection difficult even if their intensities were several times that of the 7.26 Mev. γ-ray. Radiations emitted in the reaction $Li^7(n, \gamma)Li^8$, $Q = 2.037$ Mev., are also of too low energy to be detected with the present instrument.

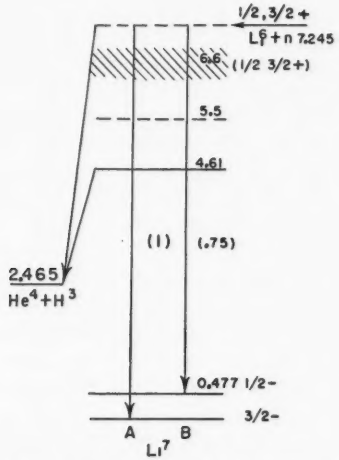

FIG. 2. Decay scheme for Li^7. The level diagram is from Ajzenberg and Lauritsen (1955). The relative intensities of the γ-rays are shown in brackets.

In order to obtain an estimate of the radiative capture cross section of Li^6, measurements were made of the intensities of the 7.26 Mev. lithium γ-ray and the 9.0 Mev. nickel γ-ray emitted from a sample containing a mixture of weighed amounts of Li_2CO_3 and Ni_2O_3. In an attempt to avoid the possibility of random clumping of the Li_2CO_3 powder, which would result in some degree of self-shielding of the lithium, the mixture was diluted by mixing in an approximately equal volume of finely divided graphite powder. By a method which has been described previously (Kinsey and Bartholomew 1953), the absolute intensity of the nickel γ-ray has been calibrated against that of the 2.75 Mev. γ-ray from Na^{24} at equilibrium. The lithium–nickel intensity comparison, after suitable corrections are applied for the spectrometer sensitivity and for absorption of the γ-rays, thus leads to a value for the partial cross section for the production of the 7.26 Mev. γ-ray, $\sigma(n, \gamma_0)$, which is proportional to the value adopted for the cross section of Na^{23}. Using 0.505 ± 0.010 barn* (Hughes and Harvey 1955) for the latter quantity, this measurement

*This value, which was obtained by pile oscillator methods, has been used in this determination because the probable error is smaller than that given for the cross section determined by activation, 0.53 ± 0.02 b. (Hughes and Schwartz 1957). The 0.505 b. value is also used in the determination of the cross sections of B^{10} and N^{14} below.

yields 0.016 ± 0.004 barn for $\sigma(n, \gamma_0)$. If then it is assumed that the 7.26 and 6.78 Mev. radiations are the only γ-rays emitted in appreciable quantities in the $Li^6(n, \gamma)Li^7$ reaction a measure of their relative intensities leads to an estimate of the radiative capture cross section of Li^6. After correcting for the spectrometer sensitivity and γ-ray absorption, the ratio of the intensity of the 6.78 Mev. γ-ray to that of the 7.26 Mev. γ-ray was found to be 0.75 ± 0.20, whence the radiative capture cross section of Li^6 is found to be 0.028 ± 0.008 barn.

BORON

The boron spectrum was examined between 3 and 11.5 Mev. Because of the weakness of the γ-rays, long counting times were required and, generally speaking, only those parts of the spectrum which showed clear evidence of peaks in a preliminary survey were selected for more detailed examination in subsequent trials. The spectrum obtained by combining all of the data is shown in Fig. 3. By comparison with the background spectrum it is possible to recognize six γ-rays which can be ascribed to boron. The presence of two of these, denoted by D and E in Fig. 3, was demonstrated clearly only in separate experiments with the modified counter apertures using a resolution of about 2%. These γ-rays were not observed in background experiments with the same resolution. It may be noted that there is a slight increase in the counting rate between 5 and 6 Mev. in the boron spectrum as compared to the background spectrum in the same energy region. While this effect may be due to the presence of a number of weak boron γ-rays there is no clear evidence of resolved peaks, and in view of the long counting periods it seems more probable that the discrepancy is produced by a fluctuation in the sensitivity of the spectrometer. The ground state γ-ray from the $B^{11}(n, \gamma)B^{12}$ reaction has an energy of 3.36 Mev. Although there is some suggestion of a peak at this energy in Fig. 3 the evidence is insufficient to identify this radiation with certainty. The carbon γ-ray at 4.95 Mev., which is very prominent in the background spectrum, is reduced in intensity in the boron spectrum because of the depression in the neutron flux produced by the nearby boron. Other background γ-rays, such as those from iron, are not similarly reduced because they originate in parts of the experimental hole which are some distance from the sample. The bismuth γ-ray at 4.17 Mev., which is produced by a bismuth shielding block situated between the sample and the core of the reactor, is reduced in intensity partly by the flux depression and partly by absorption of the γ-ray in the boron sample.

The energies of the boron γ-rays corrected for recoil and their intensities relative to that of the 4.47 Mev. γ-ray are given in Table I. Because of the poor statistics and high background the probable error of the relative intensity values is estimated to be $\pm 40\%$.

The partial capture cross section for the production of the relatively intense 4.47 Mev. γ-ray was measured by the nickel comparison method. For this experiment a sample consisting of a mixture of weighed amounts of finely powered B_4C and Ni_2O_3 was employed. A microscopic examination of the

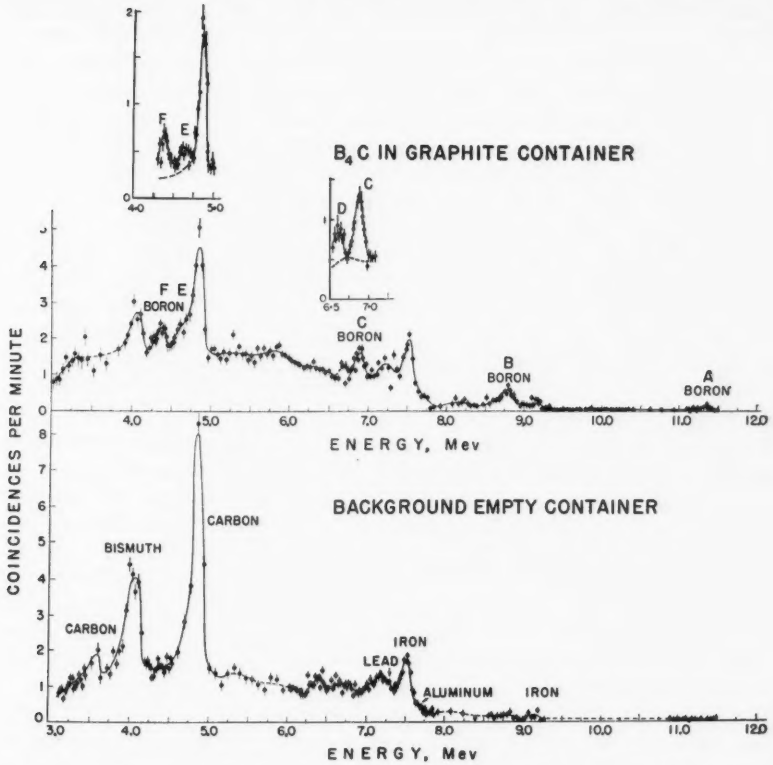

FIG. 3. Upper curve, γ-ray spectrum from boron. Lower curve, background spectrum. Insets show separate experiments to verify presence of weak γ-rays, see text. The approximate position of the background is shown by broken curves in insets.

TABLE I

NEUTRON CAPTURE γ-RAYS FROM BORON

γ-Ray	Energy, Mev., corrected for recoil	Relative intensity
A	11.43±0.04	0.01
B	8.91±0.03	0.07
C	6.98±0.03	0.22
D	6.74±0.03	0.12
E	4.73±0.03	0.40
F	4.47±0.02	1.0

grain size of the B_4C powder showed that most grains had a diameter of approximately 0.0002 inch. Since the absorption length of a thermal neutron in B_4C is about 0.005 inch, we conclude that self-shielding in the B_4C particles themselves was not important. To reduce the possibility of self-shielding

caused by clumping of the B_4C particles and to ensure a more uniform mixing of the Ni_2O_3 and B_4C, the mixture was diluted by mixing in an approximately equal volume of powdered graphite. The value obtained for the cross section for the production of the 4.47 Mev. γ-ray is 0.40 ± 0.14 barn. It will be shown below that the absolute intensity of the 4.47 Mev. γ-ray is 0.80 ± 0.15 γ-rays per radiative capture. Combining these values we find that the total radiative cross section of B^{10} is 0.5 ± 0.2 barn.

The energy levels in B^{11} may be reached by a large number of reactions (Ajzenberg and Lauritsen 1955). The most accurate values for the level energies are those of Van Patter, Buechner, and Sperduto (1951) and Elkind (1953). The γ-ray decay of many of the levels has been studied in the $Li^7(\alpha, \gamma)B^{11}$ reaction by Jones and Wilkinson (1952, see also Ajzenberg and Lauritsen 1955), in the $B^{10}(d, p\gamma)B^{11}$ reaction by Bent *et al.* (1955), and Sample *et al.* (1955), and in the $Li^7(He^3, p\gamma)B^{11}$ reaction by Ferguson and co-workers (1957). Some information on the spins and parities of some of the excited states has been obtained by Jones and Wilkinson (1952), and from the $B^{10}(d, p)B^{11}$ stripping reaction by Evans and Parkinson (1954), Paris *et al.* (1954), Cox and Williamson (1957), and Lee and Wall (1957). The spins of none of the levels would appear to be established with certainty (Ajzenberg and Lauritsen 1955), the indicated assignments being 4.46 Mev., $5/2-$; 6.81 Mev., $3/2-$; 8.93 Mev., $3/2$ or $5/2$; 9.19 Mev., $5/2-$; and 9.28 Mev., $5/2+$.

The extremely weak γ-ray, A, at 11.43 ± 0.04 Mev. is emitted in the ground state transition in B^{11}. Its energy may be compared with the neutron binding energy of B^{11}, 11.462 ± 0.011 Mev., which is calculated from the Q of the $B^{10}(d, p)B^{11}$ reaction (Van Patter and Whaling 1954). The remaining γ-rays may be assigned to transitions between the B^{11} levels as shown in Fig. 4. The full arrows indicate the γ-ray assignments which seem to be most reasonable on energy grounds. Broken arrows are used to indicate an alternative assignment for γ-ray E, and to represent γ-rays which were not observed but for which intensity limits can be given.

It would appear from the intensity of the 4.47 Mev. γ-ray that a large fraction of the cascade transitions in this reaction stop over at the second excited state. This level is fed only about 20% by the direct 6.98 Mev. transition from the capturing state and the remaining transitions must involve cascades from other excited states. One might account for the strong intensity of the 4.47 Mev. radiation by postulating that the 4.47 Mev. γ-ray from the second excited state is in cascade with a γ-ray of almost the same energy emitted in the transition from the 8.93 Mev. level to the second excited state. This latter transition, however, would appear to be ruled out by measurements of the γ-rays from the $Li^7(\alpha, \gamma)B^{11}$ reaction (Jones and Wilkinson 1952) and the $Be^9(He^3, p\gamma)B^{11}$ reaction (Ferguson *et al.* 1957) which show that the 8.93 Mev. level decays almost exclusively by the direct transition to the ground state. By the same argument we may rule out the possibility that the 6.74 Mev. γ-ray, D, is emitted in the transition from the 8.93 Mev. level to the first excited state and can therefore assign it unambiguously to the decay of the 6.76 Mev. level. Again, the same authors show that the 6.76 Mev. level is not fed strongly

by transitions from any of the higher levels up to 9.28 Mev. (Feeding from levels between 9.28 Mev. and the capturing state will presumably be negligible, for not only are the primary transitions to these levels energetically unfavored but also, for all levels in this region, γ-rays must compete with alpha-emission.) We may then deduce that part, at least, of the 4.73 Mev.

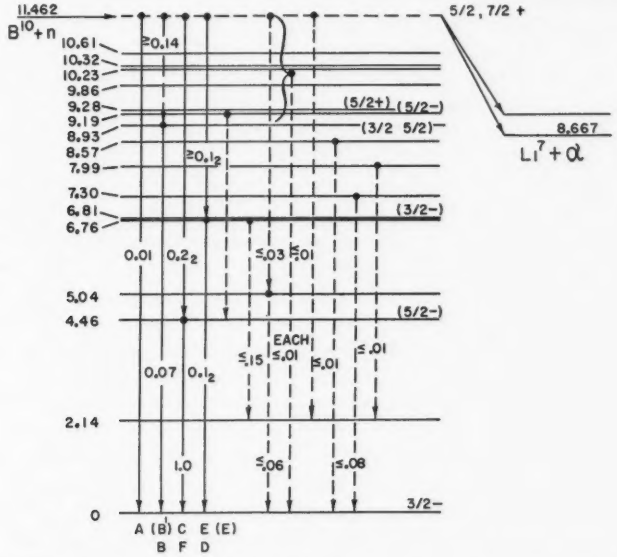

FIG. 4. Decay scheme for B^{10}. The level diagram is from Ajzenberg and Lauritsen (1955). Relative intensities of the γ-rays are shown on the arrows.

radiation, E, observed in the present experiment is emitted in the transition from the capturing level to the 6.76 Mev. level. Accordingly in Fig. 4 we have assumed that the intensity of the 4.73 Mev. transition is at least equal to that of the 6.74 Mev. γ-ray. It is perhaps worth noting that the energies of the γ-rays D and E are sufficiently accurate to exclude their assignment to the nearby 6.81 Mev. level; the corresponding γ-rays involving that level must be at least three times weaker. For the same reason it would be difficult to admit the assignment of the 4.73 Mev. γ-ray to the transition from either member of the 6.8 Mev. doublet to the first excited state. A more plausible alternative explanation for the 4.73 Mev. γ-ray is that it is emitted in the transition from the 9.19 Mev. level to the second excited state. A γ-ray of this energy has been observed to follow deuteron bombardment of B^{10} and has been assigned to the 9.19–4.46 Mev. transition in B^{11} by Bent *et al.* (1955) and Sample *et al.* (1955). From the intensity measurements we may conclude that few of the γ-rays feeding the ground state have escaped detection. The most conspicuous unknown intensity is that of the 2.14 Mev. γ-ray from the decay of the first excited state. This energy is too low to be detected with the

present instrument. However, we can surmise that the intensity of this radiation cannot be strong, for it has been shown by Jones and Wilkinson (1952) and Ferguson *et al.* (1957) that the 2.14 Mev. level is fed by only very weak transitions from the levels at 4.46 and 5.04 Mev. and the present results show that cascade γ-rays from higher levels are also of low intensity. Allowing for a weak excitation of the 2.14 Mev. level, we estimate from the results of Table I and Fig. 4 that the 4.47 Mev. γ-ray accounts for $(80\pm15)\%$ of the transitions to the ground state.

Since B^{10} has a spin of 3 and even parity the B^{11} capturing state can be $5/2+$ or $7/2+$, or both if more than one resonance contributes to the thermal capture cross section. The ground state γ-ray, which is mostly $E1$ for $5/2+$ and $M2$ for $7/2+$, will therefore be strong or weak depending on whether the former or latter spin predominates. The 4.46 Mev. level is shown to be most probably $5/2-$ or $3/2-$ by Cox and Williamson (1957) while Jones and Wilkinson find $5/2-$ (Ajzenberg and Lauritsen 1955). Assuming the $5/2-$ value, the 6.98 Mev. γ-ray, C, then is of $E1$ type regardless of the spin of the capturing state. Similarly the assignment of the 6.76 Mev. level is not known with certainty but it is probably either $5/2-$ or $7/2-$ (Cox and Williamson 1957), whence the 4.73 Mev. γ-ray, E, emitted in the transition to this level is also probably $E1$ regardless of the spin of the capturing state. (There is also presumably a relatively strong 2.53 Mev. γ-ray feeding the 8.93 Mev. level. The possibility that this level is fed by one or more cascade transitions through higher levels, all of which are unstable against alpha-emission, seems much less likely.) The relative weakness of the ground state γ-ray, A, compared with competing γ-rays, which are probably of $E1$ type, then strongly suggests that at thermal energies neutrons are captured predominantly into a $7/2+$ state and only very weakly into a $5/2+$ state. This conclusion is in accord with the explanation adduced by Inglis (1951) to account for the anomalous relative intensities of the ground state and first excited state alpha-particle groups in the $B^{10}(n, \alpha)Li^7$ reaction.

Two other deductions from the present results are perhaps worth noting. Firstly, if we assume following Cox and Williamson (1957) that the 6.76 Mev level is $5/2-$ or $7/2-$, then the presence of a strong ground state transition from this level shows that either the 6.76 Mev. level is in fact $5/2-$ or the observed γ-ray is of $E2$ type. Secondly, although our data by no means provide proof, the absence of direct transitions from the capturing state to the first and third excited states favors assignments of low spin ($1/2$ or $3/2$) for these levels and the fact that the 8.93 Mev. level is fed appreciably lends support to the $5/2$ spin assignment in this case.

We can derive order of magnitude estimates of the radiation widths of the 11.43, 6.98, and 4.73 Mev. γ-rays if we assume a plausible value for the alpha-particle width of the resonance responsible for capture. Inglis (1951) has shown that the behavior of the $B^{10}(n, \alpha)Li^7$ reaction at low neutron energies may be understood for values of Γ_α lying in the region between 1 kev. and 50 kev. Assuming an alpha-particle width of say 10 kev. and using $\sigma(n, \alpha)$, $\sigma(n, \gamma)$, and the relative intensities given in Fig. 4 we then obtain $\Gamma_\gamma = 0.01$,

0.2, and about 0.1 ev. for these γ-rays respectively. From the relative intensities of the protons producing the 8.93 Mev. level and of the γ-rays emitted in its decay as reported by Sample *et al.* (1955) it may be inferred that the alpha-particle width and γ-ray width for this level are approximately equal. A similar result was obtained by Ferguson *et al.* (1957). Hence we may deduce that the intensity of the presumed 2.53 Mev. γ-ray feeding this level in the present reaction is about twice that of the 8.91 Mev. γ-ray and that Γ_γ for the 2.53 Mev. γ-ray is therefore about 0.1 ev. Of these four γ-rays emitted by the capturing state only the first has a value of $|M|^{2*}$ very much lower than the average for $E1$ γ-rays in light elements (Wilkinson 1956).

NITROGEN

Two nitrogen samples consisting of melamine ($C_3H_6H_6$) and of urea (NH_2CONH_2), each weighing about 1.5 kg., were used. The samples were enclosed in Dural containers with graphite ends. The combined spectrum, which was examined between 3 and 11.2 Mev., is shown in Fig. 5. Parts of the spectrum near 8.5 Mev. and between 3 and 3.8 Mev. were examined under conditions of higher counting rate and poorer resolution to verify the presence of weaker γ-ray peaks at these energies. These spectra are shown in insets in Fig. 5. In addition, the shapes of the peaks at 5.29 and 5.56 Mev. were examined with the modified slit arrangement (resolution 1.2%) in an attempt to determine whether or not both members of the first excited state doublet in N^{15} were fed by direct transitions from the capturing state. The results of this examination are given in Fig. 6. Both peaks show discontinuities along the high energy slope which are too large to be attributed to chance fluctuations in counting rate. These breaks were observed consistently in repeated examinations with the modified slits and were also discerned, although less clearly, in experiments with the original slit arrangement. In Fig. 6 the experimental points are fitted with a full curve obtained by adding together standard curves corresponding to monoenergetic γ-rays. The standard curves were obtained by normalizing and averaging the peak shapes obtained with the same slit arrangement for the 3.918 and 6.756 Mev. γ-rays from neutron capture in magnesium and titanium respectively. In fitting the composite curve both the relative heights and the separations of the standard peaks were varied to obtain the best agreement. This analysis of peak shape does not provide a very accurate determination of the relative intensities of the component γ-rays since almost as good a fit may be obtained with a considerable range of intensity ratios. Thus, although it is apparent that the components of both doublets are of comparable intensity, the actual ratios indicated in Fig. 6 are tentative.

In addition to the doublet structure of γ-ray peaks G and H, the present investigation shows the presence of four weak γ-rays at 9.03, 8.54, 3.669, and 3.520 Mev. which were not detected in the earlier investigation (Kinsey, Bartholomew, and Walker 1951), and also shows that the γ-ray previously

*The quantity $|M|^2$ is the ratio of the experimental width to the theoretical single-particle width defined by Weisskopf (1951).

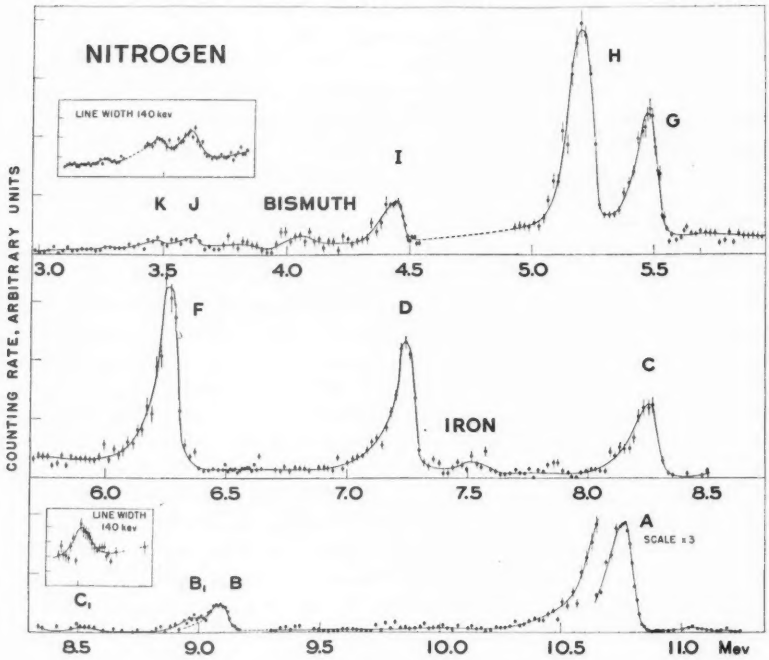

FIG. 5. γ-Ray spectrum from nitrogen.

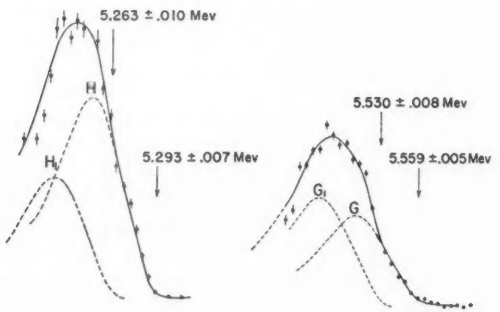

FIG. 6. Spectra of 5.29 and 5.56 Mev. N^{15} doublet γ-rays, resolution 1.2%. The broken curves are standard peak shapes which have been adjusted in position and size so that their sum (full curves) agrees with the observed data.

noted at 7.16 Mev. is not present or, at least, is very much weaker than was previously reported. The γ-ray at 9.03 Mev. is superposed on the tail of peak B in Fig. 5. The contribution from the tail is indicated by a broken curve. The 3.669 Mev. γ-ray, J, has the same energy as a capture γ-ray from carbon. However, we estimate that the intensity of the latter γ-ray, produced by neutron capture in the carbon in the sample material and graphite ends of the container, is less than one tenth of that of J. The peaks at 7.57 and 4.1 Mev. can be attributed to iron and bismuth background radiation respectively. The iron peak intensity sets an upper limit for the intensity of the possible 7.57 Mev. transition from the level at that energy to the ground state in N^{15}. There is some indication of a weak γ-ray at 7.9 Mev. in Fig. 5. However, this peak is probably caused by a statistical fluctuation in the counting rate since it was not found in a second scan over this energy region.

TABLE II

NEUTRON CAPTURE γ-RAYS FROM NITROGEN

γ-Ray	Energy, Mev., corrected for recoil	Absolute intensity, γ-rays per 100 radiative captures	Energy from $N^{14}(d, p)N^{15}$, Mev.[c]
A	10.833±0.008	11	10.841±0.007
	>9.152[a]	Each < 0.3	
B	9.152±0.010	1	9.165
B_1	9.03 ±0.03	0.2	9.062
C_1	8.54 ±0.04	0.2	8.571
C	8.313±0.013	4	8.315±0.006
D	7.305±0.012	9	7.309±0.006
E	7.57 ±0.03[b]	0.7	7.575
	(7.164)	< 0.8	
F	6.323±0.008	17	6.328±0.006
G	5.559±0.005	14 } 32[d]	5.563±0.010
G_1	5.530±0.008	18 }	5.537±0.010
H	5.293±0.007	35 } 57[d]	5.305±0.006
H_1	5.263±0.010	22 }	5.276±0.006
I	4.497±0.011	16	4.512±0.010
J	3.669±0.016	17	3.677±0.010
K	3.520±0.016	15	3.528±0.010
	(3.267)	< 6	

[a] All γ-rays between 9.152 and 10.833 Mev.
[b] This radiation is ascribed to background. Its intensity represents an upper limit for the 7.57 Mev. nitrogen transition.
[c] Sperduto *et al.* (1954), Van Patter and Whaling (1954), Malm and Buechner (1950).
[d] Intensities of component γ-rays are tentative.

The energies, corrected for recoil, and the absolute intensities of the observed γ-rays are given in Table II. The absolute intensities are obtained from the observed relative intensities with the assumption that all of the γ-rays feeding the ground state have been detected. Since all such γ-rays have energies above 5.26 Mev. this assumption seems well justified. For those γ-rays represented by strong peaks in Fig. 5 the accuracy of the absolute intensities given in Table II is probably not better than ±20%, the main source of the uncertainty being the energy dependence of the sensitivity of the pair spectrometer (Kinsey and Bartholomew 1953). The intensities corresponding to the weaker peaks may be in error by as much as 50%.

The radiative capture cross section of nitrogen has been obtained by the nickel comparison method, using samples consisting of mixtures of urea and Ni_2O_3 and melamine and Ni_2O_3. A method in which nitrogen γ-ray intensities are compared to that of the 6.8 Mev. beryllium γ-ray from a target of beryllium nitride is less trustworthy since chemical analysis of our material has shown the beryllium–nitrogen ratio to be different from that given by the formula and to be non-uniform throughout the sample. The average value obtained from the urea–nickel and melamine–nickel comparisons is 0.08 ± 0.02 barn.*

In Table II the observed γ-ray energies are compared with the corresponding energies obtained from the (d, p) reaction. The neutron binding energy of N^{15} may be obtained from the energy of γ-ray A and from the sums of the energies of four pairs of cascading γ-rays (Fig. 7). The weighted mean value is 10.831 ± 0.008 Mev., where the 8 kev. error takes account of an estimated systematic contribution to the error of each measurement. This value, which is in agreement with another measurement of comparable accuracy already published (Kinsey and Bartholomew 1953), may be compared with that obtained from both the (d, p) reaction and mass measurements. The weighted mean of eight Q-value determinations for the ground state proton group in the $N^{14}(d, p)N^{15}$ reaction is 8.614 ± 0.007 Mev. (Van Patter and Whaling 1954), whence we obtain 10.841 ± 0.007 Mev. for the neutron binding energy of N^{15}. The recent very precise mass measurements (Scolman *et al.* 1956) yield the value 10.831 ± 0.002 Mev. It will be noted that the present neutron binding energy and the γ-ray energies in Table II are somewhat lower than the corresponding (d, p) values, though the differences are, in general, less than the probable error of the present measurements. The reason for this trend is not clear.

The neutron capture γ-rays may be fitted to the N^{15} level scheme as shown in Fig. 7. The γ-rays feeding levels above 7.58 Mev. have energies too low to be observed in the present experiment. The 1.88 Mev. γ-ray shown in the decay of the 7.16 Mev. level was observed in the $N^{14}(d, p)N^{15}$ reaction by Thompson (1954). It is to be noted in Fig. 7 that such a low energy transition accounts very well for the decay of the 7.16 Mev. level and for the difference in the combined intensities of the doublet γ-rays H and G. The decay scheme is in complete accord with that obtained by Bent *et al.* (1955), who studied the high energy γ-rays following the $N^{14}(d, p)N^{15}$ reaction.

Of the excited states below the neutron binding energy the spin values are given in Fig. 7 only for those at 10.71 and 10.81 Mev., which are assigned $3/2-$ (Bartholomew *et al.* 1955).† For most of the lower levels the parities

*The result obtained in the earlier investigation (Kinsey, Bartholomew, and Walker 1951) using beryllium nitride is brought into fair agreement with the above value when corrections are applied to take account of the more accurately known spectrometer sensitivity and absolute intensity of the beryllium γ-ray (Bartholomew and Kinsey 1953).

†*Note added in proof.*—The negative parity assignment for the 10.71 and 10.81 Mev. levels is based on evidence for a multipole mixture in the angular distribution of the γ-ray to the $1/2-$ ground state of N^{15} in the $C^{14}(p, \gamma)N^{15}$ reaction. Whereas the deviation of the measured distribution from that expected for $E1$ radiation is well outside the probable error for the 10.71 Mev. level, the same cannot be claimed at 10.81 Mev. In view of the possibility that some weakening of the correlation at 10.81 Mev. could be produced either by the presence of an isotopic contribution from distant levels or by an unknown systematic error, it is now felt that the measurement does not in fact exclude a $3/2+$ assignment for the 10.81 Mev. level.

and range of possible spins may be derived from measurements of the l_n values from the $N^{14}(d, p)N^{15}$ stripping reaction. Such measurements have been made by Gibson and Thomas (1952), Sharp *et al.* (1955), Green and Middleton (1956), and Warburton and McGruer (1957). The l_n values for levels above 5.31 Mev.

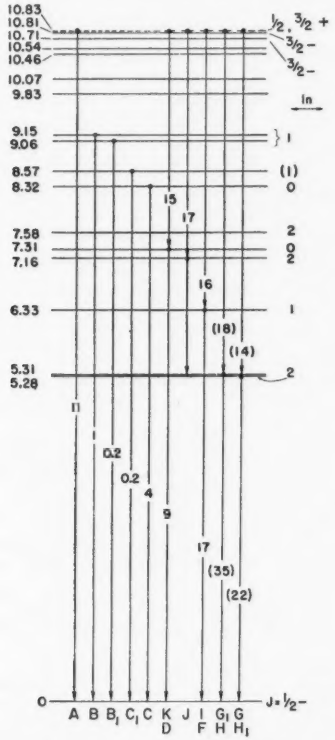

FIG. 7. Decay scheme for N^{15}.

shown in Fig. 7 are taken from the most extensive report, viz., Green and Middleton (1956). The other authors agree with the l_n values of Green and Middleton at all levels except 8.57 Mev., where $l_n = 0+2$ is favored. For the 5.31 and 5.28 Mev. levels, which were not resolved by Green and Middleton, Sharp *et al.* (1955) found an isotropic non-stripping distribution and a distribution giving $l_n = 2$ respectively. Unfortunately the present γ-ray decay scheme does not assist greatly in resolving the spin ambiguities; the only exception being the spin of the 7.16 Mev. level for which values of J less than 5/2 would appear to be excluded by the γ-ray decay as pointed out by Thompson (1954) and by Bent *et al.* (1955). Recently Halbert and French (1957) have given a theoretical account of the even parity levels of N^{15} up to an excitation energy of 12.2 Mev. using a shell model calculation. For the

first seven positive parity levels these authors predict the spin assignments of 5/2, 1/2, 7/2, 3/2, 5/2, 1/2, and 3/2 with the possibility that the third and fifth could be interchanged. The present results are consistent with these assignments. We may note however that, if these theoretical spin values are correct, either the capturing state* is predominantly 3/2+ or its decay involves the emission of $E2$ radiation of strength comparable to that of the $E1$ γ-rays emitted in transitions to the ground state and third excited state.

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*Since N^{14} is 1+ the capturing state can be 1/2+ or 3/2+. The level responsible for thermal radiative capture has not been identified (Bartholomew *et al.* 1955; Halbert and French 1957).

NEUTRON CAPTURE GAMMA RAYS FROM FLUORINE, MAGNESIUM, GALLIUM, BROMINE, AND HAFNIUM[1]

P. J. Campion and G. A. Bartholomew

ABSTRACT

The neutron capture γ-ray spectra of fluorine, magnesium, gallium, bromine, and hafnium have been studied in the energy range above 3 Mev. In fluorine four γ-rays and in magnesium 12 γ-rays have been detected in addition to those previously observed. Most of these new radiations can be assigned to the known level schemes of the product nuclei. The spectrum obtained for each of the other elements is complex with only a few of the high energy γ-rays resolved, and in each case the γ-ray of highest energy is very weak and difficult to distinguish from the background. The most energetic gallium γ-ray at 7.73 ± 0.02 Mev. may be emitted in the direct ground state transition in Ga^{70} while the 7.879 ± 0.013 Mev. γ-ray from bromine probably corresponds to the ground state transition in Br^{80}. In hafnium none of the observed γ-rays can be identified with a ground state transition in any of the isotopes.

INTRODUCTION

Some earlier measurements of the neutron capture γ-ray spectra of fluorine and magnesium have been published (Kinsey, Bartholomew, and Walker 1951*a*). In the present paper we give more detailed data for these elements together with the spectra of gallium, bromine, and hafnium which have been investigated for the first time.

The γ-rays were detected in a pair spectrometer, and the experimental arrangement and the methods of measurement were similar to those described in previous publications (Kinsey, Bartholomew, and Walker 1951*a*; Kinsey and Bartholomew 1953*a*). In the present work a line width, defined as the full width of a γ-ray peak at half maximum, of about 100 kev. was used. This line width was roughly constant over the energy range investigated, viz., 3–11 Mev. In some cases use was made of a modified slit arrangement (Bartholomew, Campion, and Robinson, to be published) in front of the stilbene crystal detectors. This gave a line width which was a constant fraction of the energy, and a resolution of 1.2% was chosen. This provided a satisfactory compromise between resolution and coincidence counting rate.

The method of measuring the absolute intensities of γ-rays by the nickel comparison method has already been described (Kinsey *et al.* 1951*a* and 1953*a*). Although the comparison is made against nickel as a substandard the ultimate standard is the 2.75 Mev. γ-ray from the decay of Na^{24} which is emitted with an intensity of one photon per capture when radioactive equilibrium is established. The only cross sections appearing in the calculation of the intensities are thus those of sodium and the element under study. Where applicable in the present paper, for the sake of continuity, we adopt the sodium cross section, 0.54 barn, which has been used for the calculation of absolute intensi-

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Contribution from Physics Division, Atomic Energy of Canada Limited, Chalk River, Ontario.
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ties in past publications from this laboratory* (Kinsey and Bartholomew 1953*a*). For gallium, bromine, and hafnium, in which many of the γ-rays have not been resolved, the corrected spectra, i.e., curves giving $\nu(E)$, the number of γ-rays per capture per energy interval, as a function of energy, are presented. For fluorine and magnesium, which have small capture cross sections, the contributions to the observed spectrum from pile background radiation are significant and difficult to subtract accurately. For this reason, and also since the γ-rays are mostly resolved in these spectra, the $\nu(E)$ curves are of little value and have not been given. Unless otherwise noted the tabulated intensities for peaks which are well resolved and strong in the uncorrected spectra are estimated to be accurate to $\pm 30\%$, while for partially resolved peaks or weak peaks the error may be as large as a factor of 2.

FLUORINE

The fluorine sample consisted of about 3.5 kg. of Teflon (C_2F_4) in an aluminum container with graphite ends. Spectroscopic analysis of the Teflon showed only trace amounts of boron, iron, magnesium, and sodium, and no radiations from these elements were found. In the earlier experiment (Kinsey *et al.* 1951*a*) aluminum radiations from the sample container masked all but the ground state γ-ray in the fluorine spectrum. This interference was avoided with the present sample container, and four previously unobserved fluorine γ-rays were detected.

The γ-ray spectrum was measured with a resolution of 1.2% over the region 3.5 to 6.6 Mev. and scanned over the region 6.6 to 7.8 Mev. using a line width of 140 kev. The complete spectrum is shown in Fig. 1. The weak peak at 7.6 Mev. is produced by neutron capture in iron in the experimental hole in the pile shield. Similarly the residual counting rate between the fluorine γ-ray peaks, which is observed with comparable intensity when no sample is present, can be largely ascribed to background radiation from the reactor. The counting rate of the γ-ray at 4.94 Mev. can be accounted for entirely by neutron capture in the carbon present in the Teflon and in the graphite ends of the sample container. The energies, corrected for recoil, and intensities of the resolved fluorine γ-rays are summarized in Table I. The intensities were obtained by comparing the intensity of the 6.80 Mev. γ-ray from beryllium with peak B using a sample of beryllium fluoride. The intensity of the 6.80 Mev. radiation was assumed to be 0.75 photons per capture (Bartholomew and Kinsey 1953), while the cross sections of beryllium and fluorine were taken as 10 mb. and 9 mb. respectively (Hughes and Harvey 1955). The intensities of the γ-rays in Table I are probably accurate to $\pm 40\%$.

The energy levels of F^{20} have been investigated by several authors using the (d, p) reaction (Allen and Rall 1951; Burrows *et al.* 1951; Shull 1951; and

*This value is close to the most recent activation cross section for sodium, 0.53 ± 0.02 b. (Hughes and Schwartz 1957), but is rather higher than the pile oscillator value, 0.505 ± 0.010 b. (Hughes and Harvey 1955). The absolute intensities are simply proportional to the sodium cross section used in the computation and can be corrected to a newly adopted value for this quantity by multiplying by the appropriate ratio. In an accompanying paper (Bartholomew and Campion 1957) we have used the more accurate value, 0.505 b., for the calculation of the radiative capture cross sections for Li^6, B^{10}, and N^{14}.

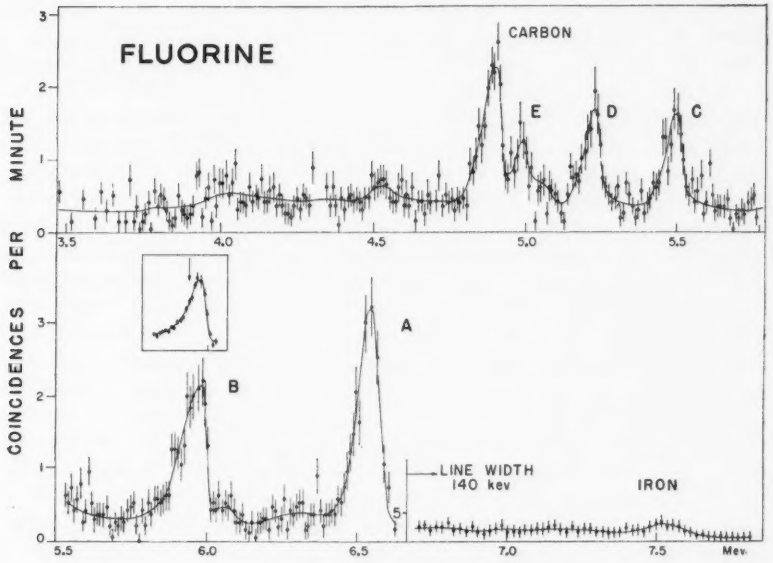

FIG. 1. Gamma-ray spectrum from fluorine.

Watson and Buechner 1952). The last-named authors, who have made the most accurate energy determinations, examined the levels in the region below 5 Mev. El Bedewi (1956) and Bromley *et al.* (1953) have used the same reaction to study the angular distribution of the proton groups. The energy resolution in El Bedewi's experiments was about 60 kev. and the energy range extended up to 7 Mev. in F^{20}. From the angular distribution results the parity and range of spin values for many of the observed F^{20} levels were determined.

The γ-ray A, when corrected for recoil, has an energy of 6.600 ± 0.011 Mev., which is in agreement with the previous observations (Kinsey *et al.* 1951*a*) and with the binding energy of F^{20} obtained from the $F^{19}(d, p)F^{20}$ reaction. Watson and Buechner (1952) quote 4.373 ± 0.007 Mev. for the Q value of the ground state transition in the latter reaction and this, together with the binding energy of the deuteron, 2.227 ± 0.002 Mev. (Van Patter and Whaling 1954), yields 6.600 ± 0.007 Mev. for the binding energy of F^{20}.

TABLE I

NEUTRON CAPTURE γ-RAYS FROM FLUORINE

γ-Ray	Energy, Mev., corrected for recoil	Intensity in photons per 100 captures
A	6.600 ± 0.011	30
B	6.019 ± 0.011	16
C	$5.54\ \pm0.02$	24
D	$5.28\ \pm0.02$	27
E	$5.10\ \pm0.02$	14

The energy of γ-ray B is 6.019 ± 0.011 Mev., which, if this radiation is emitted by the capturing state, corresponds to a transition to a level at 0.581 ± 0.013 Mev. This value does not agree with the energy of the first excited state obtained from the (d, p) reaction. For this quantity Watson and Buechner (1952) obtained 0.652 ± 0.008 Mev., while other values are 0.63 ± 0.05 Mev. (Burrows *et al.* 1951), 0.64 ± 0.03 Mev. (Allen and Rall 1951), and 0.69 Mev. (Shull 1951). Gamma-ray B has been detected in four different measurements using the Teflon sample. It was also confirmed in the spectrum from the BeF_2 sample used for the intensity calibration, and it is therefore unlikely that it is due to an impurity. Considering that the energy discrepancy is 70 kev. for the transition to the first excited state it seems more reasonable to conclude that this γ-ray represents the de-excitation of a level at 6.019 Mev. This energy is in rather poor agreement with that of a level at 5.95 ± 0.02 Mev. observed by El Bedewi (1956). The inset in Fig. 1 shows the result of a detailed search for a γ-ray of 5.948 Mev. corresponding to the transition between the capturing level and the first excited state. The expected end-point is indicated by an arrow. By comparing the shape of peak B obtained in this measurement with that due to a homogeneous γ-ray we can place an upper limit of 1 photon per 100 captures on the intensity of the 5.948 Mev. transition. Similarly no conclusive evidence could be found for radiations to the second and third excited states. These γ-rays, which would appear at 5.77 and 5.61 Mev. in Fig. 1, have intensities less than 3 and 7 photons per 100 captures respectively.

Peaks C and D have energies which correspond to transitions from the capturing level to the 1.06 and 1.31 Mev. excited states. It is also possible that part of peak D is produced by the de-excitation of the level at 5.27 Mev. (El Bedewi 1956). Peak E, 5.10 Mev., is more difficult to interpret as no corresponding low lying level is known at 1.50 Mev. Alternatively γ-ray E may be emitted in a transition to the ground state from a level at 5.10 Mev. The level nearest to this energy observed by El Bedewi (1956) is at 5.04 Mev. No further prominent coincidence peaks were found down to 3.5 Mev. Fig. 2 shows the observed γ-rays fitted to the energy level scheme.* The dashed transitions indicate tentative assignments.

The spin of the capturing state in F^{20} is 0 or 1 (or a mixture of both) with even parity. The spin alternatives for the first three excited states (El Bedewi 1956) are 1, 2, and 3 with even parity. The failure to observe γ-rays corresponding to direct transitions to any of these three levels is not inconsistent with these spin and parity data, and for the first excited state in particular the absence of a direct transition suggests that the assignment is probably 2 or 3+ but not 1+. The fourth excited state is 0, 1+ (El Bedewi 1956), and γ-ray C, which can be ascribed to the direct transition to this state, is observed. Higher states to which relatively strong $E1$ transitions could occur are the odd parity levels at 2.870 and 2.966 Mev. The primary γ-rays feeding these levels would have energies of 3.73 and 3.63 Mev. No radiations at these energies can be clearly distinguished above the background. However, because of the

Note added in proof.*—A number of additional levels in F^{20} have been reported by L. M. Kromchenko (Zhur. Eksptl. i Teoret. Fiz. **32, No. 2, 194 (1957)).

low sensitivity of the pair spectrometer at these energies, such radiations would probably escape detection unless their intensities were at least twice that of the ground state γ-ray, A. If on the other hand these radiations are in fact

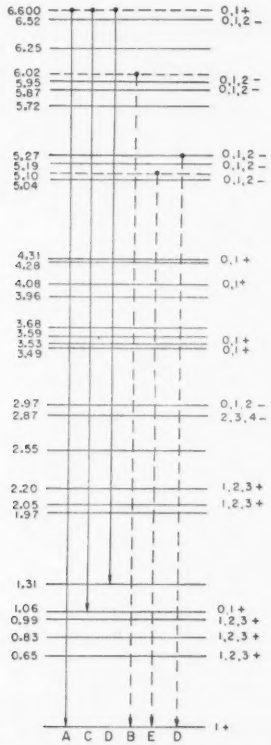

FIG. 2. Decay scheme for fluorine γ-rays. The level energies below 5.04 Mev. are from the compilation of Ajzenberg and Lauritsen (1955) while those at 5.04 Mev. and above are from the results of El Bedewi (1956). The spin and parity assignments are due to El Bedewi and to Bromley *et al.* (1953). *Note added in proof.*—Recent measurements show that the spin of the ground state is not necessarily 1 (Seward, F. D., Slaus, I., and Fulbright, H. W. 1957. Phys. Rev. **107,** 159).

absent, a possible explanation for the high population of the 5.10 and 6.02 Mev. levels would be that the capturing state is predominantly 0+ and the 5.10 and 6.02 Mev. levels are the lowest 1− levels which can be reached by $E1$ transitions.

MAGNESIUM

The magnesium sample consisted of 4 kg. of the pure metal.* The spectrum

*We are indebted to the Division of Physical Metallurgy, Department of Mines and Technical Surveys, Ottawa, for providing this sample of magnesium.

was scanned from 2.6 to 11.5 Mev. using a line width of 100 kev. while particular sections of the spectrum were investigated in closer detail with the better resolution afforded by the modified slits. In addition, the presence of some weak high energy radiation was confirmed by decreasing the resolution in order to increase the counting rate. The spectrum is shown in Fig. 3 in which regions given special attention are shown in insets. Except for perhaps the region

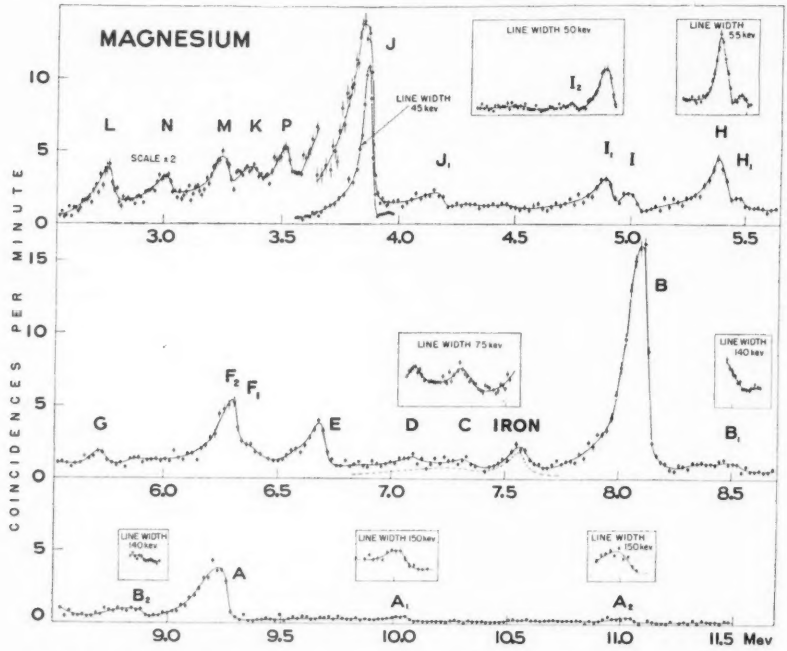

FIG. 3. Gamma-ray spectrum from magnesium. The background between 6.8 and 7.8 Mev. is shown by a broken curve.

below 4 Mev., the residual counting rate between peaks may be ascribed largely to the general background radiation from the reactor. The more intense γ-rays were observed in the earlier work (Kinsey *et al.* 1951*a*; Kinsey and Bartholomew 1953*b*). In the present experiment the improved resolution and sensitivity afforded by a substantial increase in neutron flux and an increased sample size has led to the resolution of 12 additional weak γ-rays. The energies, corrected for recoil, and the absolute intensities of the resolved magnesium γ-rays are given in Table II.

The absolute intensity of γ-ray J was remeasured by comparing its intensity with that of the 9.0 Mev. radiation from nickel, using a mixture of weighed quantities of Ni_2O_3 and MgO. Assuming a magnesium cross section of 63 ± 4 mb. (Hughes and Harvey 1955) we find that the absolute intensity of J is

47 photons per 100 captures in natural magnesium. This is considerably lower than the previous value of 94 photons per 100 captures (Kinsey *et al.* 1951*a*) which was later revised to 70 photons per 100 captures (Kinsey and Bartholomew 1954). Because of improvements in the method of measurement the

TABLE II

NEUTRON CAPTURE γ-RAYS FROM MAGNESIUM

γ-Ray	Energy, Mev., corrected for recoil	Intensities in photons per 100 captures in natural magnesium
A_2	11.089±0.025	0.03
A_1	10.08 ±0.02	0.04
A	9.282±0.013	0.5
B_2	8.93 ±0.02	0.06
B_1	8.55 ±0.02	0.06
B	8.149±0.010	3
C	7.36 ±0.03	0.06
D	7.16 ±0.03	0.11
E	6.735±0.015	1.2
F_1	6.440±0.008[a]	0.9
F_2	6.358±0.008[a]	2.4
G	5.76 ±0.02	0.6
H_1	5.51 ±0.02	0.6
H	5.442±0.012	3
I	5.05 ±0.02	1.7
I_1	4.93 ±0.02	2.7
I_2	4.77 ±0.03	0.6
J_1	4.21 ±0.02	2.5
J	3.918±0.004[a]	47
K	3.408±0.015	5
L	2.816±0.015	24
M	3.290±0.010	9
N	3.054±0.012	9
P	3.552±0.014	8

[a]Previously determined energy (Kinsey and Bartholomew 1953*b*).

present estimate is to be preferred to these earlier values. The intensities of the remaining γ-rays were determined relative to that of J using the known efficiency curve for the pair spectrometer.

The abundances, isotopic capture cross sections, and contributions to the total cross section for the magnesium isotopes are given in Table III.

TABLE III

ABUNDANCES AND CROSS SECTIONS OF MAGNESIUM ISOTOPES

Target nucleus	Abundances, per cent	Isotopic capture cross section in millibarns	Percentage contribution to total cross section
Mg^{24}	78.6	33±10[a]	46
Mg^{25}	10.1	270±90[a]	49
Mg^{26}	11.3	25± 2[b]	5

[a]Pomerance (1952).
[b]Lyon and Lazar (1956).

The earlier work on the energy levels of the magnesium isotopes has been compiled by Endt and Kluyver (1954). The most accurate energy determinations are those of Endt *et al.* (1952*a*), who used both the (d, p) and (d, α) reactions for Mg^{25}, and Endt *et al.* (1952*b*), who used the (d, p) reactions for Mg^{26} and Mg^{27}. The $Mg^{25}(d, p)Mg^{26}$ reaction has also been studied by Kromchenko (1953). Holt and Marsham (1953) have made spin and parity assignments from a study of (d, p) angular distributions in all three isotopes. Similar experiments have been performed by Hinds *et al.* (1957) using a Mg^{24} target. The γ-rays emitted in the energy range 0.3 to 3.0 Mev. following thermal neutron capture in natural magnesium have been examined by Braid (1956). The γ-ray decay of the first four excited states of Mg^{25} has been studied from the positron decay of Al^{25} (Maeder and Stähelin 1955) and the beta decay of Na^{25} (Maeder and Stähelin 1955; Iwersen and Koski 1955). More recently the γ-rays from these decays and also from the $Mg^{25}(p, p'\gamma)Mg^{25}$ reaction have been studied by Gove *et al.* (1956), who have concluded that the levels at 0.98 and 1.96 Mev. are $3/2+$ and $5/2+$ respectively while that at 1.61 Mev. is probably $7/2+$.

In Fig. 4 the observed γ-rays are fitted to the level schemes of the three

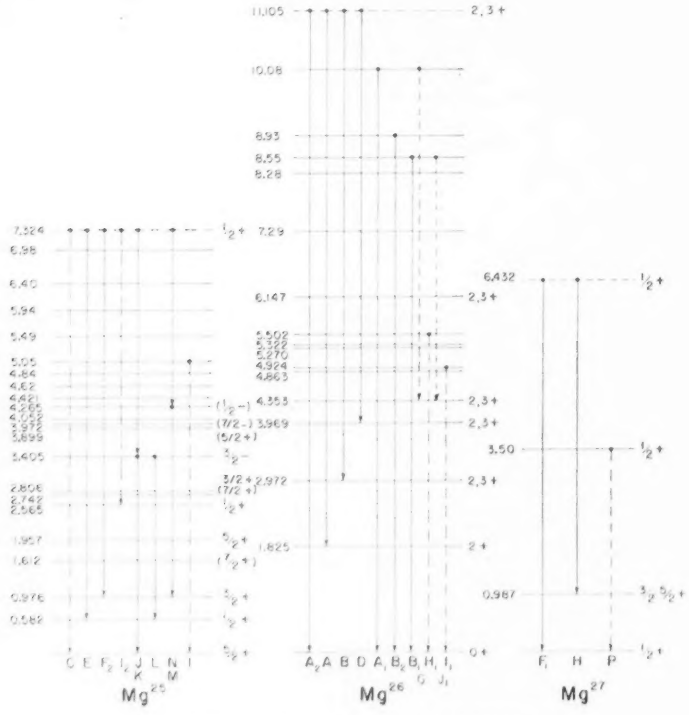

FIG. 4. Decay schemes for magnesium isotopes.

product nuclei as listed in the compilation by Endt and Kluyver (1954). The level positions found in Mg^{25} by Kromchenko (1953) and Hinds *et al.* (1957) agree with this level diagram and with each other only for energies below 4.4 Mev. Since none of the levels above this energy appear to be strongly excited in the present reaction we have for the sake of uniformity indicated only the levels of Endt and Kluyver (1954) in this region. For most of the stronger γ-rays the present more accurate measurements confirm assignments which were made in earlier work (Kinsey *et al.* 1951*a*, 1954). The four weak γ-rays at 11.09, 10.08, 8.93, and 8.55 Mev., which were not observed previously, must all belong to Mg^{26} since their energies exceed the binding energies of both Mg^{25} and Mg^{27}. It will be shown below that the 11.09 Mev. γ-ray has an energy equal to the neutron binding energy in Mg^{26} and it may be identified therefore as the ground state transition in that nucleus. The other three radiations cannot be assigned to transitions involving known low energy levels in Mg^{26} and must presumably be emitted in transitions from levels at 10.08, 8.93, and 8.55 Mev. to the ground state. The background radiation under peak C, obtained by comparison with the nearby iron peak, is shown by a broken curve in Fig. 3. The shape of peak C, shown with higher resolution in the inset, suggests that this radiation is complex. This observation was confirmed in several additional scans over this energy region. Hence, although this peak has approximately the energy required for the ground state γ-ray in Mg^{25}, we cannot now attribute the entire intensity to that transition and the intensity of C, 0.06 photons per 100 captures, thus represents an upper limit for the intensity* of the ground state γ-ray in Mg^{25}. Of the other weak coincidence peaks observed in the present experiment only G, J_1, and P are difficult to assign to positions in the decay schemes. As shown in Fig. 4, it is possible to account for G and J_1 as transitions to the fourth excited state in Mg^{26} from the levels at 10.08 and 8.55 Mev. respectively. Alternatively G may be emitted in the decay of a level of spin $1/2-$ or $3/2-$ observed at 5.79 Mev. in Mg^{25} by Hinds *et al.* (1957). Part of J_1 may be due to neutron capture in the bismuth plug situated behind the sample. It would appear that only part of peak P can be assigned to the transition in Mg^{27} shown in Fig. 4 since the intensity of this radiation exceeds the contribution of Mg^{26} to the total cross section listed in Table III.

Since Mg^{24} has zero spin and even parity the capturing state in Mg^{25} is $1/2+$ and the only levels which may be expected to be fed appreciably by direct primary transitions are those with spin and parity of $1/2\pm$, $3/2\pm$, or possibly $5/2+$. In the decay scheme for Mg^{25} in Fig. 4 the γ-ray assignments, which are based only on considerations of level energies, are also consistent with the known spins and parities for the levels. With the pair spectrometer it is possible to detect cascade γ-rays from only two of the excited states. The γ-rays K, 3.408 Mev., and L, 2.816 Mev., which have been reported earlier

*In a previous communication (Kinsey and Bartholomew 1954) attention was drawn to the ratio of transition probabilities of γ-rays C and J, which are both emitted by the capturing state and which are of $E2$ and $E1$ type respectively. In view of the present uncertainty concerning the identity of C we can now specify only an upper limit for this ratio, viz., 0.02% evaluated at 7 Mev.

(Kinsey *et al.* 1951*a*, 1954), are undoubtedly emitted in the decay of the 3.405 Mev. state. The present measurements give the intensity ratio of L to K as 5 ± 2. It is interesting to compare this value with the corresponding ratio of about 6 found in the mirror nucleus Al^{25} (Litherland *et al.* 1956). The comparatively strong intensities of transitions N, 3.054 Mev., and M, 3.290 Mev., suggest that the intermediate level at 4.265 Mev. is the analogue of the $1/2-$ level at 3.85 Mev. in Al^{25}. This interpretation is in agreement with the (d, p) stripping results (Hinds *et al.* 1957), which show that the ingoing neutron has an l_n value of unity for this level. By inverting the order of γ-rays M and N the present results could also be interpreted as a cascade through the 4.052 Mev. level, although in this case the energy fit is less satisfactory. Litherland *et al.* (1956) report the branching ratio of γ-rays from the 3.85 Mev. level in Al^{25} to the second excited state and first excited state to be 2. In Mg^{25} no transition of 3.683 Mev. from the 4.265 Mev. level to the first excited state was detected, however, and from an examination of the spectrum we deduce that the corresponding ratio in this nucleus is >3.

It is quite apparent that the decay of Mg^{26} proceeds mostly by multiple cascade transitions. The sum of the absolute intensities of those high energy γ-rays which are ascribed to transitions to the ground state, i.e., γ-rays A_2, A_1, B_2, B_1, H_1, and I_1, is only about 4% in natural magnesium. This accounts for only about one-tenth of the estimated contribution of Mg^{25} to the total cross section (Table III). Braid (1956) has shown that the intensities of the γ-rays emitted in the decay of the first and second excited states are 22 and 13% respectively. Since these levels are fed by direct transitions from the capturing state with intensities of only 0.5 and 3% we must conclude that the first and second excited states are fed strongly by transitions from other levels below the capturing state. It seems rather strange that no strong radiations which could be assigned to such transitions from any of the known levels of Mg^{26} have been detected. This may be because all such γ-rays would have energies on the borderline for sensitive detection with the pair spectrometer. On the other hand it is possible that the high population of the low energy excited states is produced by a large number of transitions none of which are particularly strong. It seems plausible that in Mg^{26}, as in Mg^{25}, the levels which combine most strongly with the capturing state are those which can be reached by $E1$ transitions. None of the levels measured by Holt and Marsham (1953) have odd parity, and while these authors made no assignments for any of the group of levels between 4.35 and 6.15 Mev. it may be that the first odd parity levels which can be reached by $E1$ transitions from the capturing state are in fact above 6.15 Mev. In any case, since levels with both $2+$ and $3+$ may be contributing to thermal capture, $E1$ transitions could occur to odd parity levels with spins 1, 2, 3, and 4. Of these, only those with spin 1 will decay directly to the ground state and the others will decay to low energy levels with spins 2, 3, etc. The large diversity of transitions possible with this scheme would account for the high population of the lower levels and the absence of strong single transitions feeding these states. It seems quite likely, moreover, that the three levels at 8.55, 8.93, and 10.08 Mev. are $1-$ levels,

for when allowance is made for possible alternative modes of decay from these levels it is apparent that the matrix elements of the transitions feeding them are considerably greater than those of the $M1$ γ-rays A and B. Unfortunately it is not possible to detect γ-rays emitted in transitions from the levels at 8.55, 8.93, and 10.08 Mev. to the low lying excited states; γ-rays emitted in transitions to the first excited state, for example, would be partially obscured by γ-rays B, D, and E.

It is of interest to compare the neutron binding energies of the magnesium isotopes obtained in the present experiment with those obtained by other methods. Such a comparison is given in Table IV, where, in order to obtain a best (n, γ) value for each isotope, we have made use of level energies determined by (d, p) and (d, α) measurements. These level energies correspond to

TABLE IV

NEUTRON BINDING ENERGIES OF Mg^{25}, Mg^{26}, AND Mg^{27} IN MEV.

	(n, γ) Present results				
Nucleus	Determination	Value	(d, p)	Mass	
Mg^{25}	γ-Rays J+K	7.326±0.016			
	γ-Ray E+0.583±0.004[a]	7.318±0.016			
	γ-Ray F_2+0.976±0.005[a]	7.334±0.009			
	Average	7.329±0.009	7.324±0.007[c]	7.331±0.002[d]	
Mg^{26}	γ-Ray A_2	11.09 ±0.02			
	γ-Ray A+1.825±0.005[b]	11.11 ±0.02			
	γ-Ray B+2.972±0.010[b]	11.121±0.014			
	γ-Ray D+3.969±0.010[b]	11.13 ±0.03			
	Average	11.113±0.012	11.107±0.012[b]	11.094±0.002[d]	
Mg^{27}	γ-Ray F_1	6.440±0.008			
	γ-Ray H+0.987±0.006[b]	6.429±0.014			
	Average	6.437±0.007	6.434±0.006[b]	(6.467±0.008)[e]	

[a]Endt *et al.* (1952*a*).
[b]Endt *et al.* (1952*b*).
[c]Van Patter and Whaling (1954).
[d]Scolman *et al.* (1956).
[e]See text.

relatively small differences in reaction Q values, and systematic errors are probably reduced by the subtraction. Hence the binding energies obtained by combining these differences with (n, γ) γ-ray energies should represent essentially independent determinations of the binding energy. The binding energy of Mg^{27}, which is listed with the mass data, is obtained by combining the disintegration energy of Mg^{27}, 2.591±0.007 Mev. (King 1954), and the Al^{27}–Mg^{26} mass difference (Scolman *et al.* 1956). The agreement between the (n, γ) and (d, p) measurements is very good for all three nuclei and these values also agree well with those obtained from mass spectroscopic data for Mg^{25} and Mg^{26}.

GALLIUM

The gallium sample consisted of about 400 g. of gallium sesquioxide contained in a small Bakelite cylinder mounted centrally within an aluminum

container with graphite ends. Spectroscopic analysis of the sample showed impurities to be present in concentrations less than 0.02%. The spectrum was scanned using a line width of 100 kev. over the energy range 3.0 to 8.8 Mev. and the results obtained below 8.0 Mev. are shown in Fig. 5. The

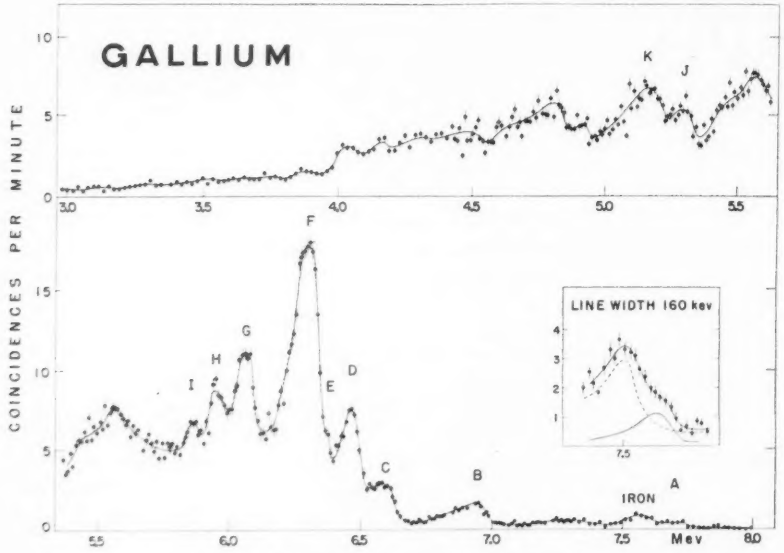

FIG. 5. Gamma-ray spectrum from gallium.

energies and intensities of the gallium radiations are listed in Table V. The absolute intensity of the peak F was determined by comparing its intensity with that of the 9.0 Mev. radiation from nickel using a mixture of weighed quantities of Ni_2O_3 and Ga_2O_3. The cross section of gallium was taken to be

TABLE V

NEUTRON CAPTURE γ-RAYS FROM GALLIUM

γ-Ray	Energy in Mev.	Intensity in photons per 100 captures in natural gallium
A	7.73 ±0.02	0.04
B	6.971±0.017	0.3
C	6.657±0.012	0.8
D	6.516±0.008	2
E	6.388±0.017	0.6
F	6.359±0.009	6
G	6.108±0.011	3
H	5.985±0.016	1.3
I	5.890±0.016	0.9
J	5.35 ±0.03	1.8
K	5.23 ±0.03	2.2

2.77 barns (Hughes and Harvey 1955). The intensities of the remaining resolved γ-rays were determined relative to that of γ-ray F. The γ-ray spectrum corrected for the sensitivity of the pair spectrometer and for absorption is shown in Fig. 6.

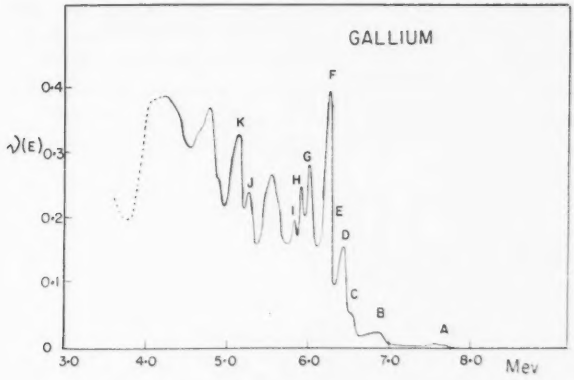

FIG. 6. Corrected γ-ray spectrum of gallium.

The weak γ-ray A is partly obscured by the iron peak which forms part of the background radiation. In the inset in Fig. 5 we show the results of a scan over this region taken with a line width of 160 kev. The dashed curve shows the iron peak observed without the gallium sample present and the full curve is the difference between the composite peak and the background. The energy of this γ-ray is 7.73 ± 0.02 Mev.

Gallium consists of two stable isotopes, Ga^{69} and Ga^{71}, which have abundances of 60.2% and 39.8% respectively and which contribute in the ratio of roughly two to three to the cross section of the natural element. The nucleus Ga^{70} is shielded and no information regarding its levels is available from β-decay. A 49-hour β-activity which is attributed to Zn^{72} has been reported by Siegel and Glendenin (1950) and the decay indicates the presence of a level in Ga^{72} at about 1.3 Mev. (Way *et al.* 1955).

The binding energies of Ga^{70} and Ga^{72} have been estimated from mass values and reaction cycles by Way *et al.* (1955). The values obtained are 7.68 ± 0.08 Mev. and 7.1 ± 0.1 Mev. respectively. It would seem therefore that only the γ-ray A can be assigned to Ga^{70} unambiguously. Since the energy of A falls within the probable error of the estimated binding energy it may be emitted in the ground state transition in that nucleus.

The ground state spin of Ga^{69} has been measured as 3/2 (Becker and Kusch 1948) and on shell model considerations this state is expected to have odd parity. The capturing level in Ga^{70} is thus 1 or 2−. There is evidence from the β-decay that the ground state spin of Ga^{70} is 1+ (Bunker *et al.* 1957) and hence one might expect an $E1$ ground state transition in the capture γ-ray

spectrum. If γ-ray A is indeed this radiation its intensity is surprisingly weak compared with other γ-rays in the spectrum.

BROMINE

The bromine sample consisted of 1.5 kg. of lead bromide in an aluminum container with graphite ends. Spectroscopic analysis of the lead bromide showed impurities to be present to less than 0.01%. The spectrum, which was measured from 3.0 to 8.25 Mev. with a line width of 100 kev., is shown in Fig. 7. Table VI lists the energies and intensities of the resolved radiations. The intensities were determined by comparing the bromine peak counting rates with that due to lead at 7.38 Mev. The γ-ray at this energy in Fig. 7

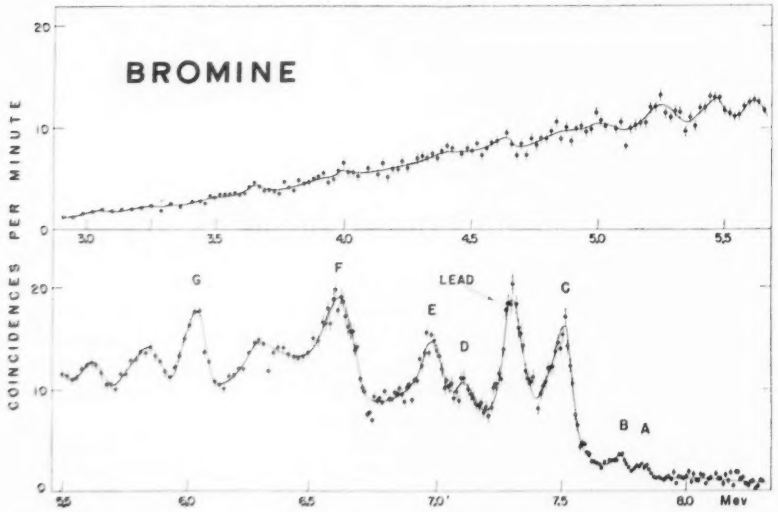

FIG. 7. Gamma-ray spectrum from lead bromide. The peak at 7.38 Mev. is produced by neutron capture in Pb^{207}.

is of normal width and we have assumed that this peak is entirely due to lead. The capture cross sections of lead and bromine were assumed to be 0.17 and 6.6 barns respectively (Hughes and Harvey 1955) and the absolute intensity of the lead radiation was taken as one photon per capture. This last assumption is justified by a previous study of the lead capture radiation (Kinsey *et al.* 1951*b*) and by the work of Adyasevich and co-workers (1955). The probable errors of the intensities quoted in Table VI are estimated to be about ±50%. The γ-ray spectrum corrected for the sensitivity of the spectrometer and for the absorption of the radiations in the sample and neutron filters in the experimental hole is shown in Fig. 8.

Bromine has two stable isotopes, Br^{79} and Br^{81}, which have abundances of 50.5% and 49.5% respectively, and which contribute to the total neutron

capture cross section of the natural element in the ratio of approximately four to one.

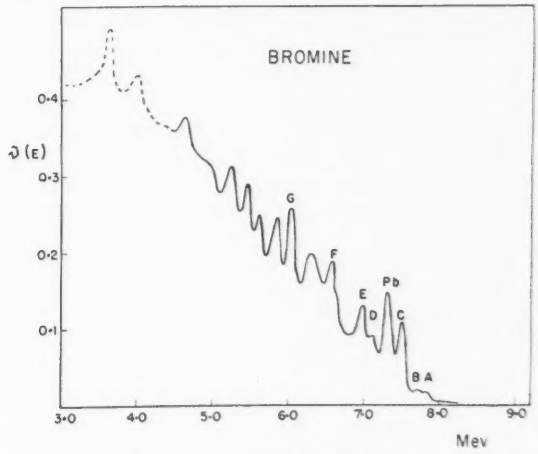

FIG. 8. Corrected γ-ray spectrum of bromine.

TABLE VI

NEUTRON CAPTURE γ-RAYS FROM BROMINE

γ-Ray	Energy in Mev.	Intensity in photons per 100 captures
A	7.879±0.013	0.15
B	7.777±0.013	0.24
C	7.579±0.012	1.6
D	7.174±0.016	0.7
E	7.046±0.016	1.0
F	6.72 ±0.02	1.0
G	6.11 ±0.02	1.1

Two levels at 84 and 36 kev. have been found in Br^{80} (see compilation by Way *et al.* 1955). The spins of these levels and of the ground state of Br^{80} have been discussed by Goldhaber and Hill (1952), who quote the assignments 5− for the 84 kev. level, 2− for the 36 kev. level, and 1+ for the ground state. From the β-decay of Br^{82} it may be deduced that this nucleus has a high spin (Way *et al.* 1955). Nothing is known about any of the other levels in either isotope. The ground state spins of Br^{79} and Br^{81} have both been established as 3/2 (Townes *et al.* 1947) and from the shell model the parity in both cases is expected to be odd. These assignments are consistent with the β-decay data for each nucleus. If the above spin assignments are correct the ground state capture γ-ray in Br^{80} is $E1$ regardless of the spin of the initial state. The estimated binding energies of Br^{80} and Br^{82} according to Way *et al.* (1955) are 7.98±0.08 and 7.8±0.1 Mev. respectively. The most

energetic γ-ray is detected at 7.879 ± 0.013 Mev. If this is the expected $E1$ ground state γ-ray in Br^{80} it is, like the corresponding high energy γ-ray in the gallium spectrum, rather weaker than one might have expected. Again because of the paucity of knowledge of the energy levels and binding energies it is not possible to identify any of the other γ-rays in the spectrum.

HAFNIUM

The hafnium sample consisted of about 400 g. of very pure hafnium oxide.* The spectrum was scanned with a line width of 100 kev. over the energy range 3.5 to 8.4 Mev. The results are shown in Fig. 9. The γ-rays A at 7.62 Mev. and B at 7.33 Mev. have energies very close to those of prominent

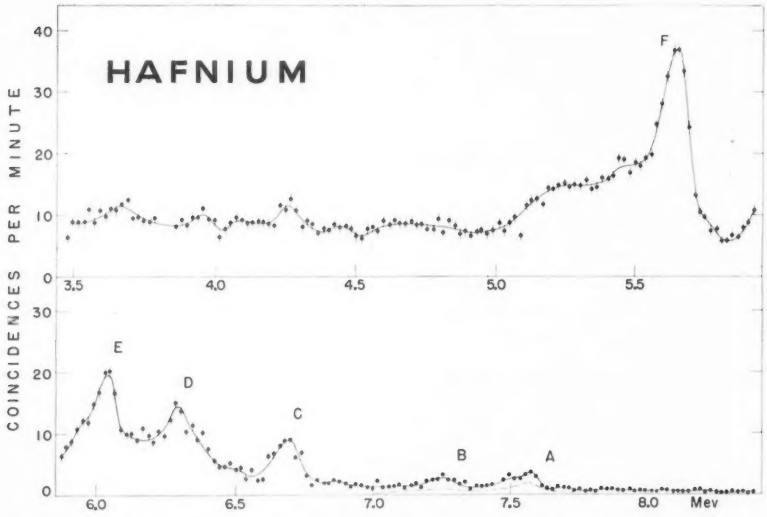

FIG. 9. Gamma-ray spectrum from hafnium. The background between 7 and 7.7 Mev. is shown by a broken curve.

background γ-rays from lead and iron. However the intensities of A and B are at least twice as great as those expected for the background γ-rays in this experiment and there can be little doubt that they are produced in hafnium. The energies and intensities of the resolved γ-rays are listed in Table VII. The absolute intensity of peak F was found by comparing its counting rate with that of the 9.0 Mev. radiation from nickel using a mixture of weighed quantities of Ni_2O_3 and HfO. The cross section of hafnium used in this calibration was 105 barns (Hughes and Harvey 1955). The intensities of the remaining resolved γ-rays were determined relative to that of peak F. The corrected spectrum is given in Fig. 10.

*We are indebted to Dr. F. H. Spedding, Iowa State College, Ames, Iowa, for the provision of this sample.

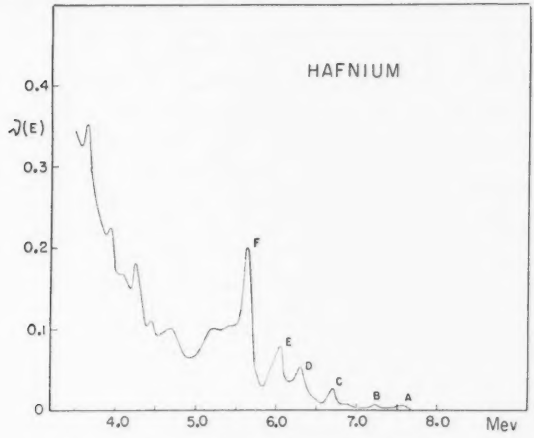

FIG. 10. Corrected γ-ray spectrum of hafnium.

TABLE VII

NEUTRON CAPTURE γ-RAYS FROM HAFNIUM

γ-Ray	Energy in Mev.	Intensity in photons per 100 captures
A	7.62 ±0.02	0.07
B	7.33 ±0.03	0.06
C	6.77 ±0.02	0.5
D	6.44 ±0.02	0.8
E	6.094±0.011	1.0
F	5.716±0.008	3.0

Hafnium consists of six stable isotopes whose percentage abundances, isotopic cross sections, and contributions to the cross section of the natural element are listed in Table VIII. Also tabulated in the last column are the recent neutron binding energies determined by mass measurements for Hf^{177}, Hf^{178}, Hf^{179}, and Hf^{180} (Johnson and Bhanot 1957) as well as the calculated values for Hf^{175} and Hf^{181} (Cameron 1957).

As can be seen from Table VIII, Hf^{177} and Hf^{178} together account for all but about 16% of the captures in natural hafnium and therefore most of the observed radiation will belong to Hf^{178} and Hf^{179}. The spins of Hf^{177} and Hf^{179} have recently been measured by Speck and Jenkins (1956) to be 7/2 and 9/2 respectively, in agreement with the predictions of Mottelson and Nilsson (1955). It follows that the ground state γ-rays in Hf^{178} and Hf^{179} will be of high multipole order and probably will not be observed. The energies of all of the observed γ-rays are considerably lower than the binding energies of Hf^{178} and Hf^{180} reported by Johnson and Bhanot (1957). Since, as shown in Table VIII, the cross section of Hf^{177} is about eight times larger than that of Hf^{179} it seems probable that γ-rays with energies above 6.63 Mev. belong to

Hf^{178}. In any case it is somewhat remarkable that there are no levels within about 1.3 Mev. of the ground state in Hf^{178} which are excited appreciably by direct transitions from the capturing state. Although some levels in the hafnium isotopes are known from studies of β-decay and Coulomb excitation it is not possible at present to assign any of the γ-rays in the observed spectrum.

TABLE VIII

ABUNDANCES, ISOTOPIC CAPTURE CROSS SECTIONS, CONTRIBUTIONS TO TOTAL CROSS SECTION, AND BINDING ENERGIES OF THE PRODUCT NUCLEI FOR THE HAFNIUM ISOTOPES

Isotope	Abundance, per cent	Isotopic cross section, barns[a]	Contribution to total cross section, per cent	Neutron binding energy of product nucleus, Mev.
Hf^{174}	0.18	1500±1000	2.5	6.44[b]
Hf^{176}	5.15	15±15	0.7	6.74[c]
Hf^{177}	18.39	380±30	65.2	8.11[c]
Hf^{178}	27.08	75±10	18.9	6.63[c]
Hf^{179}	13.78	65±15	8.4	7.86[c]
Hf^{180}	35.44	13±5	4.3	5.36[b]

[a]Hughes and Harvey (1955).
[b]Cameron (1957).
[c]Johnson and Bhanot (1957).

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ON A NEW THEORY OF MOUNTAIN BUILDING[1]

A. E. SCHEIDEGGER

ABSTRACT

In recent years there has been a growing body of evidence indicating that continental drift might have occurred on a large scale. Without prejudicing the reality of such drift (which must be decided upon from factual evidence), this paper investigates the forces that might possibly have caused it. This leads to a new theory of mountain building. It is shown that continental drifting, as it is indicated by presently available evidence, might be explained by the assumption of a *random* drag force with a correlation time of 150 million years. It is possible, though not altogether likely, that this drag force might be the result of very large (radius 6000 km.) random convection currents. Their duration would also have to be of the order of 150 million years. The assumption of a random drag force does not necessarily contradict ideas maintaining that continental growth also took place; the two effects might well be superimposed upon each other.

1. INTRODUCTION

Evidence has recently been accumulating which indicates that many parts of the world have undergone rather extensive horizontal displacements during the Earth's geological history. First of all it was paleoclimatic evidence (Köppen and Wegener 1924; Köppen 1940) which seemed to indicate that such shifts took place. Then it became known that most earthquakes throughout the world represent strike-slip faulting (Hodgson 1955; Scheidegger 1955) which is most easily explained if it is assumed that some parts of the Earth's crust are being horizontally displaced with regard to others. Furthermore, Worzel's (Worzel and Shurbet 1953) work indicating that the Mohorovičić discontinuity is not depressed beneath deep sea trenches, but implying that the latter are giant chasms in the crust, again points toward horizontal displacements of substantial extent. Finally, paleomagnetic evidence (Clegg, Deutsch, and Griffith 1956) definitely seems to indicate that large horizontal shifts of various parts of the world did indeed take place. From these various sources it seems indicated that, for example, India moved a distance of the order of 6000 km. towards America during the last 60 million years, and that, in general, the southern continents moved distances of the order of some 14000 km. from their original adjoining position ("Gondwanaland") in the Paleozoic period. From the displacement of India (assuming that India drifted only one-half of the apparent value, America the other half) it would appear that a good value for the average continental drift in recent times might be about 5 cm./year. A continent may then be thought of as a disk floating upon a denser substratum; a good model might be a circular disk of some 1000 km. radius and 40 km. thickness, the latter being suggested by the depth of the Mohorovičić discontinuity.

The postulate of crustal shifts was long ago made the central point of Wegener's (1922) continental drift "theory". However, a critical study indicates that Wegener's is not really a *theory*, but rather a *hypothesis*. In a

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theory, it would be expected that an attempt is made to explain the physical mechanism of the phenomenon in question, whereas in the continental drift "theory" only the existence of the phenomenon is asserted; the nature of the forces producing it is left open. Wegener himself suggested that possibly Eötvös' pole-fleeing force might be held responsible for the drift, but the existence of this force has long since been disproved (Prey 1936). If continental drift is real, some other force must have been its cause.

The aim of this paper is to throw some light upon the forces that might have caused continental drifting so as to make a theory out of the continental drift hypothesis. The continental drift theory becomes a theory of *mountain building*, if the crustal shortening necessary to produce mountains is thought of as being caused as a secondary effect by the converging motion of parts of the Earth's crust. Since it is thought that the explanation of the forces that might cause continental drifting is new, what is presented in this paper constitutes, in fact, a new theory of orogenesis.

When discussing theories of orogenesis, it should be kept in mind that whether continental drift did or did not occur is not an issue of theoretical geophysics; the only judgment on this question can be obtained from an analysis of geological, paleomagnetic, seismological, and other factual data. The theorist, then, has to accept whatever the verdict from these analyses is. At the present time, evidence (though it is not yet absolutely conclusive) seems to point toward the reality of continental drift; without prejudicing this reality one is therefore justified in investigating what the causes of this drift (if it took place at all) could have been.

The problem, at the present time, is therefore to find out as much as possible about the forces that could have caused continental drift, *assuming* the latter as real and of such a magnitude as is indicated at the present time from the analysis of the various types of data mentioned above. The main thesis of this paper is that such forces could be drag forces of a random nature, with an autocorrelation time of the order of 100 million years.

Theories of orogenesis are, in essence, speculations designed to fit certain data. With the addition of new data, existing theories must of necessity be abandoned and replaced by new speculations. The discovery of the transcurrent nature of earthquake faulting, for instance, has played havoc with most existing theories of mountain building (Scheidegger 1955). A similar fate will probably some day meet the present theory; in the meantime, however, no alley that might possibly prove successful in the end can be left unexplored.

2. THE RESISTANCE OF CONTINENTS TO DISPLACEMENTS

The first step in elucidating the nature of the forces that might have caused continental drifting is to determine what sort of a resistance is encountered if a continent is moved from one position to another. The motion of a continent that is being pushed around is naturally governed by Newton's law

$$m\ddot{\mathbf{x}} = -W\dot{\mathbf{x}}+\mathbf{F}. \tag{2.1}$$

Here, m is the mass of the continent, $\mathbf{x}$ its position, dots denote time derivatives, W is a coefficient indicative of the (viscous or other) resistance it encounters, and $\mathbf{F}$ is the force causing the drifting. Bold-face letters denote vectors.

It is possible to estimate the order of magnitude of the various terms, and especially to show that the inertia term ($m\ddot{\mathbf{x}}$) is insignificant. In order to do this, we assume (in accordance with Wegener's theory) that a continent is a disk floating upon a denser substratum.

The *resistance* of a circular disk of radius c moving slowly edgewise in a fluid of viscosity η is given by the following expression (Lamb 1945, p. 605):

$$W = 6\pi\eta R \tag{2.2}$$

with

$$R = 16c/9\pi = 0.566c. \tag{2.3}$$

A *floating* disk experiences only half of this resistance; hence

$$W = 3\pi\eta \frac{16c}{9\pi} = \frac{16}{3} c\eta. \tag{2.4}$$

The resistance *force* is equal to $-W\dot{\mathbf{x}}$; using the values $c = 1000$ km., $\dot{\mathbf{x}} = 5$ cm./year (see Introduction), and $\eta = 10^{22}$ c.g.s. (from the uplift of Fennoscandia; Gutenberg 1941), we have

$$W\dot{x} = 16/3\times10^{8}\times10^{22}\times5\times1/3\times10^{7} = 9\times10^{23} \text{ dynes.} \tag{2.5}$$

The *inertia force* can be calculated as follows. The mass of the model continent discussed above is (with density $\rho \sim 3$ g./cm.^{3}, $H = 40$ km. = depth of Mohorovičić discontinuity)

$$m = \rho\pi c^2 H = 3\pi\times10^{16}\times4\times10^{6} \simeq 4\times10^{23} \text{ g.} \tag{2.6}$$

In order for inertia forces to become important, one would have to have

$$m\ddot{x} \backsim W\dot{x} \tag{2.7}$$

and thus

$$\ddot{x} \simeq 2.5 \text{ cm./sec.}^2 \tag{2.8}$$

It is entirely inconceivable that the accelerations in the continental drift theory could be so high. This means that inertia forces can safely be neglected.

It therefore turns out that the force $\mathbf{F}$ causing drifting is proportional to the velocity of the continents:

$$\mathbf{F} = W\dot{\mathbf{x}} = \frac{16}{3} c\eta\dot{\mathbf{x}}. \tag{2.9}$$

One may also note that, for a given velocity $\dot{\mathbf{x}}$, the force $\mathbf{F}$ is *not* proportional to the mass or area of the continents, but only to a length connected with the latter. Thus, for various types of continents, if they are to move equally fast, the driving forces must be proportional to, say, the respective circumferences, unless the continents were so small that they would each be completely immersed in a stream of the underlying substratum.

3. THE ASSUMPTION OF A RANDOM FORCE

In order to explain continental drift, we now investigate the possibility that the driving force might be a *random force*. According to the last section, this also implies that the continents are subject to *random drifting*.

Since geological investigations lead to a *continental path*, the logical type of analysis of continental drift is the Lagrangian analysis. We assume that the mean velocity $\bar{v}$ of all the continents is zero; for the analysis, the Earth can of course be considered as flat (coördinates x, y). Thus we have

$$\bar{v}_x = \bar{v}_y = 0, \tag{3.1}$$

$$\overline{v_x^2} = \overline{v_y^2} = \tfrac{1}{2}\overline{v^2} = \text{const.}, \tag{3.2}$$

with

$$\overline{v^2} = 25\ (\text{cm./year})^2. \tag{3.3}$$

Then the total displacement of a continent evolving in time is

$$x = \int_0^t v_x(\tau)d\tau, \tag{3.4}$$

$$y = \int_0^t v_y(\tau)d\tau. \tag{3.5}$$

This leads to

$$\overline{x^2} = \overline{y^2} = \phi(t), \tag{3.6}$$

where $\phi(t)$ can be calculated as follows:

$$\overline{x^2} = \overline{\left[\int_0^t v_x(\tau)d\tau\right]^2} = \overline{\int_0^t \int_0^t v_x(\tau_1)v_x(\tau_2)d\tau_1 d\tau_2}. \tag{3.7}$$

Introducing the Lagrangian correlation coefficient

$$R_x(h) = \overline{v_x(t)v_x(t+h)}/\overline{v_x^2}, \tag{3.8}$$

relation (3.7) can be written as follows:

$$\overline{x^2} = \overline{v_x^2}\int_0^t \int_0^t R(\tau_1-\tau_2)d\tau_1 d\tau_2 \tag{3.9}$$

and, upon making a minor transformation,

$$\overline{x^2} = 2\overline{v_x^2}\int_0^t (t-\tau)R_x(\tau)d\tau. \tag{3.10}$$

The last relation has been found by Kampé de Fériet (1939). It is useful in order to investigate limit cases.

The autocorrelation time is defined as

$$L_t = \int_0^\infty R(\tau)d\tau; \tag{3.11}$$

it is the time during which an after-effect of a particular velocity value can be felt. With regard to L_t, one can investigate two limit cases. For

$$t \gg L_t \tag{3.12}$$

one obtains from (3.10)

$$\overline{x^2} = 2\overline{v_x^2}\, L_t\, t - 2\overline{v_x^2} \int_0^\infty \tau R(\tau) d\tau, \tag{3.13}$$

where the last term is a constant which can be neglected. Hence

$$\overline{x^2} \simeq 2\overline{v_x^2}\, L_t\, t \tag{3.14}$$

or ($r^2 = x^2 + y^2$)

$$\overline{r^2} = 2\overline{v^2}\, L_t\, t\,. \tag{3.15}$$

This formula for the average square of the displacement ($\overline{r^2}$) is valid for time intervals which are long compared with L_t. If we insert the estimates for the displacements and the velocity, we obtain a value for the autocorrelation time L_t. Remembering that the displacements of the pieces of "Gondwanaland" since the Carboniferous epoch ($t \sim 2.6 \times 10^8$ years) are on the average 14000 km. ($r = 14 \times 10^8$ cm.) and using the modern value for the velocity v (e.g. from the displacement of India, see Introduction) of 5 cm./year, we obtain

$$L_t = \frac{\overline{r^2}}{2\overline{v^2} t} = \frac{196 \times 10^{16}}{2 \times 25 \times 2.6 \times 10^8} \simeq 10^8 \text{ years.} \tag{3.16}$$

It may be noted that this is indeed small compared with the time since the Carboniferous epoch, as was supposed when making the calculation.

On the other hand, for very short time intervals, one obtains of course

$$\overline{r^2} = \overline{v^2}\, t^2. \tag{3.17}$$

Therefore, if the time since the Eocene (60 million years) can be regarded as "short", the time since the Carboniferous (260 million years) as "long", one can explain the order of magnitude of the drift of India and of the drift of the "pieces of Gondwanaland" simply by assuming a random drift with a velocity of, on the average, 5 cm./year and an autocorrelation time of 150 million years. It is worthy of note that the autocorrelation time is precisely of the right order of magnitude to divide "short" from "long" time intervals and thus to make the theory consistent; this can hardly be assumed to be accidental.

4. NATURE OF THE RANDOM FORCE

The discussion in the last section is essentially kinematical; i.e., in fact, not the *force* was assumed to be random, but the *velocity* of each continent. Since the resistance of each continent to flow is proportional to its circumference, the above discussion obtains if the magnitude of the random force is proportional to the circumference of the body on which it acts.

It is easy, however, to make modifications in order to take care of cases where the *force* **F** is random, but where the *velocity* **v** it produces in a certain object depends on the properties of that object. We thus introduce a K-factor such that

$$K = F_x/\dot{x}, \tag{4.1}$$

with the understanding that K is a characteristic of the body. We then have

$$K\mathbf{x} = \int_0^t \mathbf{F}(\tau)d\tau. \tag{4.2}$$

The statistical discussion of the last section, then, has to be done with **F** instead of with $\dot{\mathbf{x}}$, which simply has the effect that one has to replace everywhere in Sec. 3 **x** by $K\mathbf{x}$ and $\dot{\mathbf{x}}$ by $K\dot{\mathbf{x}}$.

From all the available evidence, it appears that all continents, regardless of their size, are drifting at similar speeds; i.e., it does not seem possible to say that, for example, all the smaller continents are drifting faster than the big ones. This would imply that the best value for the K-factor would be 1, but, of course, since the question of the *reality* of continental drift is not yet fully settled, it can even much less be expected that any definitive statements regarding the character of this drift can be made. When more is known about the details of continental drift, a better estimate can be made of the K-factor.

Knowledge of the K-factor is essential for any guess as to the *physical* nature of the forces that cause drifting. To date, we can only say that assuming them of a random nature does fit the available data. One can, of course, make further speculations and, for example, follow up an idea of Matschinski (1954) according to which the combined effect of numerous appearing and decaying convection currents is responsible for the drag. If the continents are assumed to be *large* with regard to the convection currents, then it is obvious that the effect of the latter on the former will, on the average, be zero, since the various convection cells are just as likely to pull in one direction as in any other one. However, if the continents are *small* compared with the convection cells, then the former will be totally immersed in the latter and therefore assume the surface speed of the convection current that happens to be beneath. The net effect of this argument is that the K-factor should be such that the larger the continents, the slower should be their motion. As was outlined above, it cannot yet be said whether this is actually the case. Evidence rather seems to indicate that all continents, regardless of size, move on the average equally fast. Therefore, if convection currents are the cause of the motion of continents, they should be larger than the largest continents, which would make them of some 6000 km. radius. The same 6000 km. is then also the distance over which a continent may move at uniform speed; the velocity of the current just below the surface should be equal to the average velocity of the continents, viz. 5 cm./year. The currents, thus, would have to be of gigantic extensions indeed which, in turn, makes their existence somewhat doubtful.

It is therefore at the present state of knowledge not yet possible to obtain

a more definite indication as to the actual physical nature of the drift-causing force.

5. CONCLUSION

In conclusion, let us state once more that the basic thesis of the present paper is that continental drifting, as it is indicated by presently available evidence, could be caused by a random drag force with a correlation time of 150 million years. It is possible, though not entirely likely, that this drag force might be caused by random convection currents. The size of the latter would have to be very large, viz. their radius would have to be of the order of 6000 km., which is somewhat unreasonable; their duration, naturally, would simply be of the order of the correlation time of 150 million years.

In connection with the continental drift theory it might be well to point out that the notion of large horizontal displacements of the continents does not necessarily run contrary to ideas of continental growth. The two phenomena might well be superimposed upon each other.

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AN ELECTRICAL RECORDING MAGNETOMETER[1]

P. H. SERSON

ABSTRACT

An instrument for recording at a fixed station variations in three orthogonal components of the earth's magnetic field is described. The sensitive head, containing detectors of the saturated transformer type, can be operated out of doors at the end of a long cable. A strip-chart recording meter provides a visible record of the three d-c. output signals (1 volt = 100 gammas). Calibrated baseline controls permit biasing of the magnetic detectors for any location in Canada. Tests on 10 instruments indicate a noise level of 3 gammas and a maximum drift of 10 gammas in 10 hours.

INTRODUCTION

As part of its contribution to the International Geophysical Year, the Dominion Observatory has supplied 16 stations in Canada with three-component recording magnetometers. The main purpose of the instruments is to provide the observers with an immediate indication of the degree and type of magnetic disturbance at any time. In Canada, a comparatively low sensitivity of 1000 gammas full scale (1 gamma = 10^{-5} oersted) is sufficient, and a considerable simplification of the design was possible by accepting sources of error which would not produce effects apparent at this sensitivity. The instrument is not intended to replace the usual photographic variometers at magnetic observatories, but the records collected from many stations engaged in auroral and ionospheric research should aid in the analysis of magnetic disturbances.

The instrument consists of a field-sensitive head containing three orthogonal magnetic detectors of the fluxgate type, an electronic assembly, and a recording voltmeter (Fig. 1). The magnetometer head, which may be set up out of doors, is connected to the rest of the equipment by a six-conductor cable which may be as long as a few thousand feet. The output of the instrument is in the form of three d-c. voltages proportional to the three components of the magnetic field at a scale of 1 volt per 100 gammas. To bring the output voltages on scale, the magnetic detectors can be biased by adjusting calibrated controls. The range of adjustment includes all fields likely to be encountered in Canada. The magnetometer head can be set to record declination, horizontal component, and vertical component (D, H, Z), or north, east, and vertical components (X, Y, Z), or declination, inclination, and total intensity (D, I, F).

Almost any type of recording meter can be used. Several meters can be connected in parallel to provide records at different sensitivities and chart speeds. The meter chosen for the Geophysical Year program is of the chopper-bar type, giving three rectilinear traces in different colors on a single chart. The range of the meter is -5 volts to $+5$ volts, corresponding to -500 to $+500$ gammas.

THEORY OF OPERATION

Figure 2 is a block diagram of one of the three channels of the magnetometer.

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Contribution from the Dominion Observatory, Department of Mines and Technical Surveys, Ottawa, Canada, Vol. 3, No. 14.

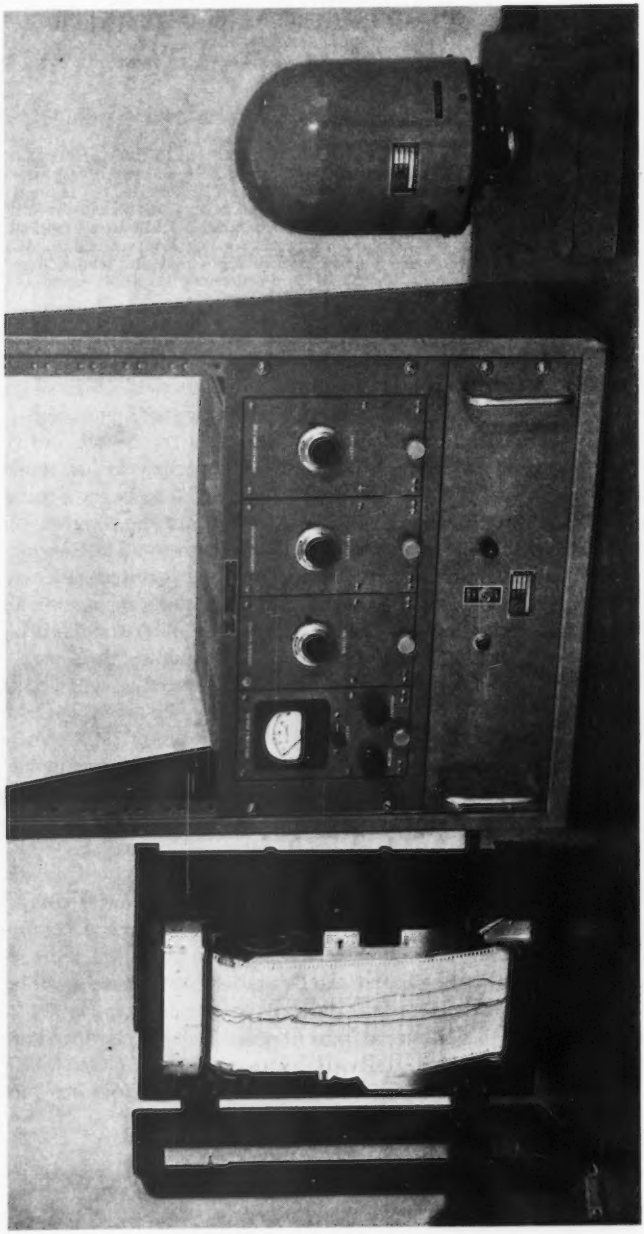

FIG. 1. Three-component recording magnetometer.

The magnetic detector contains two parallel strips of annealed Mumetal 4.0×0.10×0.014 in., each inside its own primary winding of 335 turns of number 30 wire. A common secondary winding of 2800 turns of number 30 wire surrounds the two strips. The primary windings are oppositely wound, and the Mumetal cores are carefully matched to produce a balanced assembly.

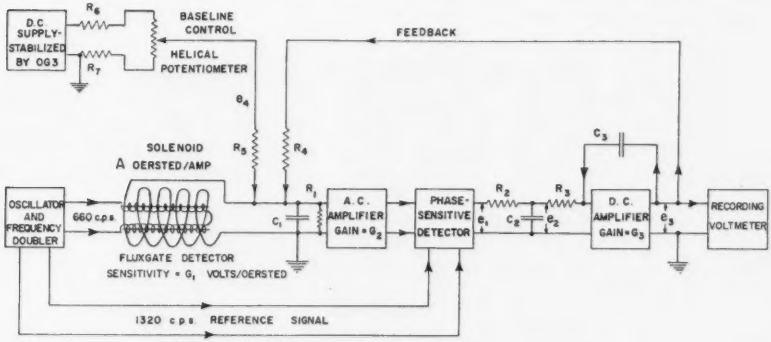

FIG. 2. Block diagram of recording magnetometer.

An oscillator supplies to the primary windings a 660-cycle excitation current large enough to saturate the Mumetal cores for about 30% of the time. Since the exciting field is at least 10^5 times larger than the magnetic field to be detected, the two cores become saturated and unsaturated simultaneously, to a very good approximation. When the cores are unsaturated, their high permeability increases the flux through the secondary winding due to an external magnetic field. When the cores become saturated, 1320 times per second, their permeability decreases, and the flux through the secondary due to the external field decreases to the value it would have if the cores were not there. Thus a voltage is induced in the secondary winding with an amplitude and phase depending on the magnitude and sense of the external magnetic field.

A capacitor C_1 is connected to the secondary winding to tune the magnetic detector to 1320 cycles per second. The alternating current circulating through C_1 and the secondary winding produces a magnetic field which reinforces the field to be detected at the appropriate instant, producing a large increase in sensitivity. A shunting resistor R_1 holds the sensitivity down to a manageable value—about 1 millivolt per gamma—and makes the device insensitive to reasonable changes in excitation current and frequency. The theory of the tuned magnetic detector has been published earlier (Serson and Hannaford 1956).

The a-c. signal from the magnetic detector is amplified and passed through a phase-sensitive detector to give a d-c. signal e_1 proportional to the magnetic field at the Mumetal cores. This signal, after being filtered, is integrated by a d-c. amplifier with capacitive feedback. The output voltage e_3 is fed back through the resistor R_4 to the secondary winding of the detector to produce a

magnetic field in the opposite sense to the field causing the signal. An adjustable voltage e_4 applied to the secondary winding through resistor R_5 produces a magnetic field equal and opposite to the normal value of the component being recorded.

Since the resistance of the secondary winding is negligibly small compared to resistances R_1, R_4, and R_5 (Fig. 2), the output of the phase-sensitive detector is given by

$$e_1 = G_1G_2\left(H-\frac{A}{R_4}\,e_3-\frac{A}{R_5}\,e_4\right),$$

where H is the component of the earth's magnetic field along the axis of the detector unit, and the other symbols are defined in Fig. 2. Two more equations are obtained by considering the currents in the capacitors:

$$C_2\,\dot{e}_2 = \frac{e_1}{R_2}-\frac{e_2}{R_2}-C_3\,\dot{e}_3$$

and

$$C_3\,\dot{e}_3 = \frac{e_2}{R_3}-\frac{e_3}{G_3R_3}.$$

By combining these three equations, the differential equation relating the output voltage to the magnetic field is obtained:

$$\frac{R_2C_2R_3C_3R_4}{G_1G_2A}\,\ddot{e}_3+\left(\frac{R_2C_2}{G_3}+R_2C_3+R_3C_3\right)\frac{R_4}{G_1G_2A}\,\dot{e}_3 + \left(1+\frac{R_4}{G_1G_2G_3A}\right)e_3 = \frac{R_4}{A}\,H-\frac{R_4}{R_5}\,e_4.$$

For $G_1 = 100$ volts/oersted, $G_2 = 200$, $G_3 = 50$, $R_4 = 340{,}000$ ohms, and $A = 340$ oersteds/ampere, the coefficient of e_3 in the differential equation is $(1+1/1000)$, and normal variations in G_1, G_2, and G_3 will have no noticeable effect on the output voltage. Inserting the actual values of resistances and capacitances, the differential equation becomes

$$1.9\times10^{-5}\ddot{e}_3+3.2\times10^{-3}\dot{e}_3+e_3 = 10^3H-5.15e_4,$$

where e_3 and e_4 are in volts, H is in oersteds, and time in seconds. The response of the system is similar to that of a simple servomechanism with inertia and viscous damping. The natural frequency is 36 cycles per second and the damping ratio 0.36 of critical. The choice of the natural frequency may seem unnecessarily high, but, in practice, the response of the instrument to rapid changes in the magnetic field is limited not by the natural frequency but by the saturation of the output of the phase-sensitive detector at about ±2 volts. Since the integrator time constant $R_3C_3 = 0.047$ seconds, the maximum rate at which the output voltage can change is 40 volts per second, corresponding to 4000 gammas per second.

DETAILS OF CONSTRUCTION

The magnetometer head clamps to the top of a length of $1\frac{3}{8}$ in. aluminum

tubing, which is set in concrete or simply driven into the ground. The head can be rotated in azimuth about a vertical axis. Three levelling screws and two level bubbles are provided to set this axis vertical to one minute of arc (Fig. 3). The X and Y fluxgates are mounted by bakelite clamps on a horizontal bakelite plate. The Z fluxgate is cemented through a hole in a second bakelite plate. The two plates are supported by three vertical threaded rods. A polyester Fiberglas cover protects the magnetic detectors from the weather.

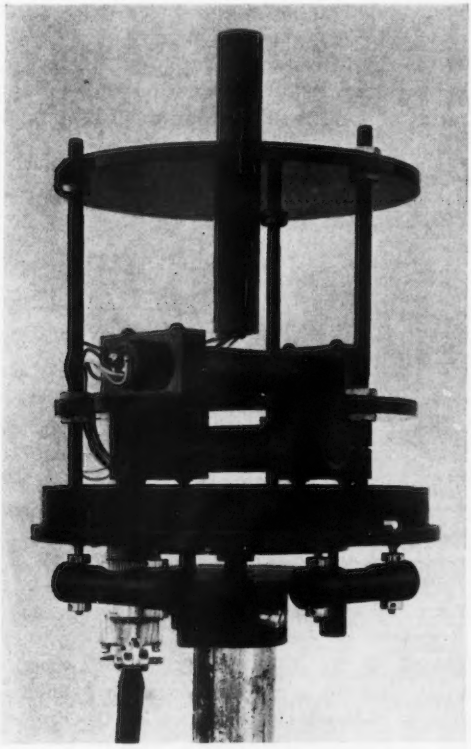

FIG. 3. Head of magnetometer with cover removed.

The axes of the detectors can be aligned quickly to an accuracy of a few minutes of arc by the following procedure. To make the sensitive axis of the Z detector parallel to the vertical axis of the head, nuts on the threaded rods are adjusted until the Z reading does not change when the head is rotated in azimuth. To make the axes of the X and Y units perpendicular to the axis of rotation, the head is mounted on a pipe which is roughly parallel to the earth's field, and the levelling screws are adjusted for zero output of the X and Y channels, with the baseline controls at zero. Nuts on the threaded rods are

then adjusted until the X and Y outputs remain at zero when the head is rotated about its axis.

The electronic assembly consists of a regulated power supply and a console containing four plug-in chassis: an oscillator and frequency-doubler unit, and three component amplifier units. This form of construction, which is due to Canadian Applied Research Limited, has proved particularly convenient in servicing. Faults can be located quickly by interchanging the plug-in chassis.

The power supply is of conventional design, with a type OD3 reference tube, type 12AX7 cascode amplifier, and a type 6Y6G series regulator. It supplies regulated outputs of $+150$ volts and -150 volts.

Figure 4 shows the circuit of the oscillator and frequency-doubler unit. A phase-shift oscillator gives a 660-cycle sine wave which is applied by a phase inverter to the grids of a push-pull output stage. The output supplies the

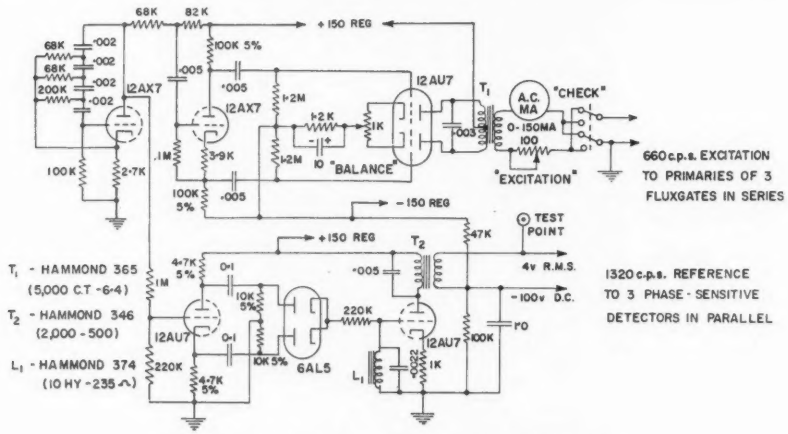

FIG. 4. Circuit of oscillator and frequency-doubler unit.

excitation current at 90 ma. through the primary windings of the three magnetic detectors connected in series. Because the Mumetal cores cannot be matched perfectly, even-harmonic distortion in the excitation current can displace the nulls of the magnetic detectors. For this reason, the control marked "Balance" is provided between the cathodes of the output stage. It is adjusted until the three channels show no change in output signal when the excitation current is reversed by the switch marked "Check".

A full-wave detector driven by the oscillator through a second phase inverter gives a 1320-cycle signal, which is filtered and amplified to provide a reference voltage for the phase-sensitive detectors in the component amplifiers.

Figure 5 shows the circuit of one of the component amplifiers. The secondary winding of the magnetic detector is connected to the input of a two-stage a-c. amplifier including a resonant circuit of low Q tuned to 1320 cycles per second. The second stage is operated with a low plate-supply voltage to avoid over-

loading on large signals of the phase-sensitive detector which follows. The d-c. amplifier consists of a balanced input stage and a cathode follower. No balancing controls are necessary, because the signal level at the output of the phase-sensitive detector is about 0.2 volts per gamma, and drift due to aging of tubes and resistors is unlikely to cause an error of more than 1 or 2 gammas.

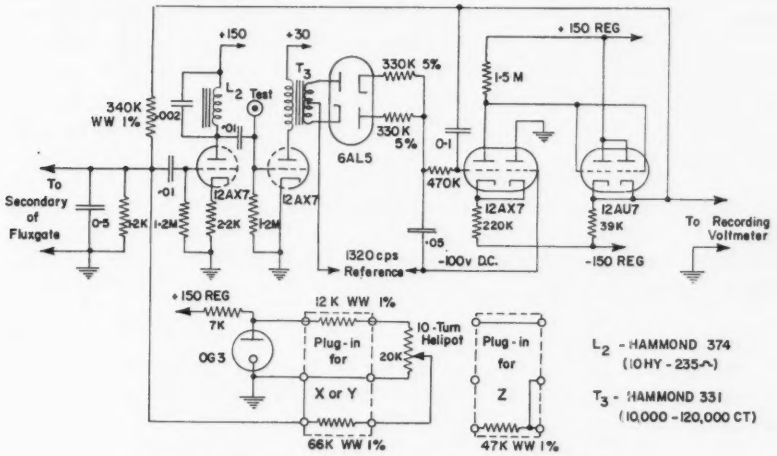

FIG. 5. Circuit of one of the three component amplifiers.

The component amplifier unit includes a 10-turn helical potentiometer for adjusting the bias current flowing through the magnetic detector. Plug-in resistor networks allow a choice of the range to be covered by this control. The networks shown in Fig. 5 give a range of 0 to 24,600 gammas for X and Y, and 43,000 to 61,500 gammas for Z.

ACCURACY

It has been shown that the sensitivity of the instrument depends on the value of a precision resistor and the solenoid constant of the magnetic detector. Since the resistor has a tolerance of 1%, and the solenoid constant depends primarily on the number of turns of wire, which can be accurately reproduced in manufacture, it is not surprising that measurements show the sensitivities of different instruments to be identical within 1%. The relation between the bias field of the detector and the setting of the helical potentiometer includes the tolerance in the output of the type OG3 voltage reference tube as well as the tolerances in the resistors and potentiometer. Baseline values can be computed from the setting of the control knob to an accuracy of ± 100 gammas $\pm 3\%$ of the baseline value.

The temperature coefficient of the solenoid constant is -0.0055% per °C., and temperature changes have a negligible effect on the sensitivity of the recording. When a large component is being recorded, however, the effect on

the bias field is noticeable. In the vertical component in Canada, the recorded value increases 3 gammas per ° C. as the temperature of the head rises. The thermal time-constant of the head is about one hour. The type OG3 voltage reference tube has a temperature coefficient of -0.003% per ° C., but since it is usually in a heated building the effect is small.

Drift in the output of the type OG3 voltage reference tubes is of the greatest importance. According to the manufacturer, the maximum drift is 0.3% over the first 300 hours, and 0.1% over 100 hours thereafter. Accordingly, drifts of the order of 50 gammas in several days are expected in the vertical component. There is no evidence of a continued drift in one direction over longer periods. Instruments have been operated for more than a year without readjusting the baseline controls.

Ten instruments were tested for noise and drift by setting them up in pairs, with the heads 1 foot apart, and recording at high sensitivity the differences between the corresponding output voltages. The result was a noise level of 3 gammas peak to peak for a band-width of 0 to 1 cycle per second, and a maximum drift of 10 gammas in 10 hours.

ACKNOWLEDGMENT

The author gratefully acknowledges the contribution of R. L. Adams of Canadian Applied Research Limited to the mechanical design of the instrument.

REFERENCES

SERSON, P. H. and HANNAFORD, W. L. W. 1956. Can. J. Technol. **34**, 232.

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CORRECTIONS

Vol. 29, 1951. In the paper *The magnetic dipole over the horizontally stratified earth* by James R. Wait, pp. 577–592,

(1) in equation (38), $2\pi\sigma\rho^4$ should read $2\pi\sigma\rho^5$;
(2) in equation (39), -6 should read $+6$;
(3) in equation (59), $\frac{3\mu dA}{4\pi}$ should read $\frac{3\mu dA}{4\pi p}$;
(4) in Appendix B, the right-hand side of the last equation should read

$$-2x^4\mathrm{erf}''(x)-2x^3\mathrm{erf}'(x).$$

Vol. 31, 1953. In the paper *A conducting permeable sphere in the presence of a coil carrying an oscillating current* by James R. Wait, pp. 670–678,

(1) in equation [5], ρ should read z;
(2) in equations [29], [30], and [31], $1/4\pi$ should be deleted;
(3) in equation [31], $3z_0^2\rho$ should read $3z_0^2q$.

Vol. 32, 1954. In the paper *On the theory of an antenna with an infinite corner reflector* by James R. Wait, pp. 365–371, the following should be noted. Since equation [4] is not an identity, equation [5] for Π_p is not the true primary field. Π_p, however, has the proper dipole singularity and, consequently, equation [7] for the total field Π is correct as given.

Vol. 32, 1954. In the paper *Calculated diffraction patterns of dielectric rods at centimetric wavelengths* by Charlotte Froese and James R. Wait, pp. 775–781,

(1) in line 14, p. 776, "incident field E_0 at P" should read "incident field E_0 at O";
(2) in equation [1], the definition of ϕ_0 is

$$\phi_0 = k[\sqrt{(x+x_0)^2+y^2}-x_0]$$

and $H_0^{(1)}[k(x+x_0)]$ should read $H_0^{(1)}[kx_0]$.

Vol 34, 1956. In the paper *Transient fields of a vertical dipole over a homogeneous curved ground* by James R. Wait, pp. 27–35,

(1) in equation (28), $-(\pi\rho)^{\frac{1}{2}}(1-\rho)$ should read $-i(\pi\rho)^{\frac{1}{2}}(1-\rho)$;
(2) in equation (31), x should read z.

Vol. 33, 1955. In *Capture radiation and neutrons from the bombardment of C^{14} with protons* by G. A. Bartholomew, F. Brown, H. E. Gove, A. E. Litherland, and E. B. Paul, pp. 441–456, the following corrections should be noted. For the resonance at $E_p = 1.50$ Mev. in Table II the radiative yield should read 490 not 49 photons/10^{11} protons. The quantity θ_n^2 for the resonance at $E_p = 2.27$ Mev. in Table V should read 0.03 not 0.007. On page 452, in the 13th line from the bottom the first quantity in brackets should read $(\hbar^2/Ma^2)$ and in the 10th line from the bottom the first word should read Gordan.

Vol. 34, 1956. For the paper *Shell effects on the spacing of nuclear levels* by T. D. Newton, pp. 804–829, the author has submitted the following correction:

There is an error in equation (14) of this paper. It should read

$$D_0 = 2(2I+1)D_{\text{obs}} \tag{14}$$

for all values of I.

This unfortunate error has been carried through the calculation so that the nine entries D_0 for targets of spin 0 in Table I and the ratios D_0(calc) to D_0(obs) for the same cases in Table III are each in error by a factor 2.

Since data from 52 nuclei were used and the fit is only to an average uncertainty of a factor 3 the constants of the best fit will not be seriously altered. The correction generally improves the fit of the spin zero target cases except for the two lead isotopes.

This mistake was shown to me by A. G. W. Cameron, who has also remarked that the levels used to define D(obs) for light and magic nuclei may include some resonances from p and d neutron absorption. If so, the estimated observed average level spacing may be too small in these cases.

Vol. 34, 1956. On p. 1151, line 3, "$(\Delta B)_{\text{unperturbed}}$ a value *larger* than $(\Delta B)_{\text{perturbed}}$" should read "$(\Delta B)_{\text{unperturbed}}$ a value *smaller* than $(\Delta B)_{\text{perturbed}}$".

Vol. 34, 1956. In *Nuclear magnetic resonance and electronic structure of conductors* by N. Bloembergen, pp. 1299–1314, a factor of one-half (1/2) has been erroneously omitted in the last term of equation (2). The discussion on page 1303 has to be modified correspondingly. The use of somewhat better values for the constants occurring in equations (2) and (3) leads to a vibrational change of the Knight shift between 200° K. and 350° K. of 0.6%, rather than 2.1% as quoted. The good agreement with the observed vibrational change of 1.5% is therefore lost.

The author is indebted to Dr. G. B. Benedek for calling his attention to the error.

Vol. 35, 1957. In the paper *Tables of certain Clebsch-Gordan coefficients and of matrix elements of P_2, P_2^2, and P_2^3 between single-particle states* by Kailash Kumar, pp. 341–345,

(1) in Table I, in the section $(jj'\,5/2\,-5/2|2\,0)$ for $j = 17/2$, $j' = j$, .20327975 should read $-.20327975$, and in the section $(jj'\,7/2\,-7/2|2\,0)$ for $j = 15/2$, $j' = j+1$, .25141195 should read .25141495;

(2) in Table II, in the section $m = 7/2$ for $j = 13/2$, $j' = j$, $-.06153845$ should read $+.06153845$;

(3) in Table IV, in the section $m = 9/2$, the numbers printed in the $j = 7/2$ column should be moved to the $j = 9/2$ column.

Vol. 35, 1957. On p. 579, in equation (2.10), $(n \pm m - 1)B_{n,m\mp1}(U_r, U_z)$ should read $(n \pm m + 1)B_{n,m\mp1}(U_r, U_z)$.

Vol. 35, 1957. In the paper *The cumulative yields of the krypton and xenon isotopes produced in the fast neutron fission of Th^{232}* by T. J. Kennett and H. G. Thode, pp. 969–979,

(1) in Table III, last line, 8.20×10^{13} and 8.28×10^{13} should both read 6.8×10^{13};

(2) in equation (4), $\exp(-n\sigma_a\lambda)$ should read $\exp(n\sigma_a\lambda)$;

(3) in the first line, p. 977, 8.6×10^{13} should read 6.8×10^{13};

(4) in Table VII, line B, 5.19×10^{16} should read 5.19×10^{15}.

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